AN ABSTRACT OF THE THESIS OF

Jeffrey D. DeBell for the degree of Doctor of Philosophy in Forest Products and Forest Science presented on June 3, 1998. Title: Wood Quality Studies in Second-growth Western Redcedar (Thuja plicata Donn.)

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Western redcedar (Thuja plicata Donn.) is a valuable commercial species found in the northwestern United States and southwestern Canada. This dissertation includes four papers focused on wood and stem characteristics of second-growth western redcedar, and how those characteristics vary within the stem or how they are influenced by cultural practices. Trees from three study sites were used these studies: 1) approximately 90-year-old trees from a naturally regenerated, unmanaged stand in northwest Oregon, 2) a 35-year-old planted western redcedar spacing trial near Vancouver, British Columbia, and 3) an approximately 30-year-old, naturally regenerated western redcedar stand that had received thinning and fertilization treatments on the Olympic Peninsula in Washington.

Characteristics studied at one or more sites include stem taper, branch diameter, incidence and severity of stem fluting, sapwood width and area, heartwood radius and area, heartwood percentage, content of tropolones (toxic extractives) in the heartwood, and decay resistance of heartwood in soil block tests.

Stem morphological characteristics such as branch size, taper and fluting increased with tree spacing. Tropolone content and decay resistance varied substantially within the stem, with the lowest levels of each usually found in wood near the pith or the top of the tree; this pattern indicates a "juvenile wood" with respect to tropolone content exists in western redcedar. Wood with high tropolone content had high decay resistance in soil block tests, while wood with low tropolone content was extremely variable in decay resistance. Heartwood and sapwood relationships varied both within the stem and between trees subjected to different cultural treatments. Within the stem, the quantity and proportion of heartwood increased from the top of the tree downward. Trees that grew faster as a result of cultural treatments had more sapwood and heartwood, and tended to have a higher proportion of heartwood compared to their slower-growing counterparts. It appears that cultural treatments can be used to exert a significant influence on wood and stem characteristics in western redcedar.

Wood Quality Studies in Second-growth Western Redcedar (Thuja plicata Donn.)

by

Jeffrey D. DeBell

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Presented June 3, 1998
Commencement June 1999

Doctor of Philosophy thesis of Jeffrey D. DeBell presented on June 3, 1998

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Jeffrey D. DeBell, Author

ACKNOWLEDGEMENTS

I am indebted to a number of people for their assistance and support of this research. Don Munro, director of the UBC Research Forest, and his staff made the western redcedar spacing trials available to me and provided me with background information. My work would not have been possible without the earlier efforts of J. Walters, who had the foresight to establish the trials, and J.H.G. Smith, who maintained and measured the trials for many years. Connie Harrington of the Pacific Northwest Research Station is the person who originally suggested the idea of working on western redcedar, and she and Harry Bell of Green Crow allowed me to sample their thinning and fertilization trials at Ozette. Bob Daniels of Forintek Canada Corporation provided tropolone standard samples and discussed extraction techniques with me at the start of my work. The samples he provided were critical to my work. Chris Biermann, Joe Karchesy and Murray Laver provided laboratory equipment and considerable technical assitance with the chemistry work. Without their help, I would not have succeeded with the tropolone analysis. Jeff Morrell, and a number of people from his lab, conducted the soil block tests for decay resistance. Their work made my tropolone data more meaningful. Hua Chen helped with gas chromatography, and conducted some additional tropolone analysis to help test the extraction methodology. My major professors and committee members, Barbara Gartner, John Tappeiner, David Marshall, Joe Zaerr, Joe Karchesy and Doug Brodie helped in a number of ways, including informal discussions, formal interrogations, reviews of my papers, and valuable advice. My father, Dean DeBell, helped with some of the measurements and provided many excellent critical discussions and reviews. My wife, Christine, helped with both field measurements and laboratory analysis, and kept things going on the home front during the many hours I spent on the computer. I am very grateful to all of these people for their help and support.

This research was funded in part by a USDA Special Grant to Oregon State University for Wood Utilization Research.

CONTRIBUTION OF AUTHORS

Barbara Gartner assisted with the study design and writing of each manuscript. Jeff Morrell arranged for the soil block tests in his laboratory and assisted with the interpretation and writing of sections dealing with decay resistance in soil block tests.

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Wood Quality Studies in Western Redcedar (Thuja plicata Donn)

Chapter 1: Introduction

Western redcedar (Thuja plicata Donn.) is a valuable commercial species found in the northwestern United States and southwestern Canada. Despite its value, most major forest landowners, in the U.S. at least, have done little to actively regenerate or manage western redcedar. However, interest in management of redcedar has increased in recent years for a number of reasons, including western redcedar's resistance to laminated root rot (Phellinus weirii (Murrill) R.L. Gilbertson), concerns for biodiversity, and the declining availability of old-growth western redcedar.

Because foresters in the region have limited experience managing western redcedar, there is little information on variation in stem characteristics of trees grown in managed stands. Stem characterstics are influenced by tree spacing or other cultural practices; some of these characteristics affect the suitability of logs for conversion into useful products. The suitability of wood for end use is often referred to as "wood quality". Attention to wood quality is important because in some cases it influences value per unit of wood in the current market, and in other cases it may influence the value or even the competitiveness of the product in the future. The following four papers provide information on some aspects of wood quality variation and the influences of cultural practices upon it in second-growth western redcedar.

Chapter 2 addresses the influence of tree spacing on several aspects of stem morphology that may be important to log and/or lumber value, including branch size, stem taper, and the degree of stem fluting.

Chapter 3 describes a modification of previously developed methods for analyzing tropolone content of western redcedar heartwood, including some pilot-scale trials to evaluate the use of tropolone content of increment cores as an indicator of decay resistance. Tropolones are chemicals found in the heartwood of western redcedar that are largely responsible for its well-known decay resistance.

Chapter 4 focuses on within-stem variation of tropolone content and decay resistance in second-growth western redcedar trees.

Chapter 5 addresses heartwood and sapwood relationships within trees as well as effects of cultural practices on these relationships.

All four papers share the common goal of increasing our understanding of wood quality variation in second-growth western redcedar, and how that variation is influenced by management practices.

Chapter 2: Stem Characteristics on the Lower Log of 35-year-old Western Redcedar Grown at Several Spacings

Jeffrey D. DeBell and Barbara L. Gartner

Reprinted from the Western Journal of Applied Forestry [1996. 12(1):9-14], published by the Society of American Foresters, 5400 Grosvenor Lane, Bethesda, MD 20814-2198.

ABSTRACT

Information on stem characteristics of western redcedar (Thuja plicata Donn.) grown in managed stands is quite limited. Stem characteristics are important because they influence the quality of logs and lumber produced. We measured branch diameter, number of branches, taper, and fluting severity on the first 5m log of stems grown at spacings of 1.8 to 4.6 meters in a 35-year-old spacing trial on the University of British Columbia Research Forest. Average branch diameter increased from 15mm to 25mm as tree spacing increased from 1.8m to 4.6m. Number of branches per unit of stem length was unaffected by spacing. Trees at wider spacings tended to be more tapered and have more butt swell than those at narrower spacings. At wider spacings, more trees showed fluting, and that fluting was more severe than at narrower spacings. However, most trees had no fluting or only mild fluting even at the 4.6m spacing. Branch diameter, taper and fluting were all related to stem diameter. Smaller diameter stems tended to have smaller branches, less taper, and were less likely to have severe fluting than large diameter stems. Branch diameter was larger at wider spacings even for trees of the same stem diameter.

INTRODUCTION

Western redcedar (Thuja plicata Donn.) is a commercially valuable tree species in the northwestern United States and southwestern Canada. Although few landowners actively regenerate and manage redcedar at present, interest is increasing for a number of reasons, including concerns for biodiversity, western redcedar's resistance to the root rot Phellinus weirii (Murrill) R.L. Gilbertson, and the declining availability of old-growth redcedar.

Foresters in the region have little experience managing redcedar, so there is not much information on variation in stem characteristics of trees grown in managed stands. Stem characteristics are usually influenced significantly by tree spacing; some of these characteristics affect the suitability of logs for conversion into useful products. The suitability of wood for end use is often referred to as "wood quality". Branch size and number, taper and fluting may be important stem characteristics affecting wood quality in western redcedar.

Branch size and number are important quality characteristics because they determine knot characteristics of wood. Knots are an important factor in determining both log and end product grades. Branch diameter usually increases with tree spacing (Haygreen and Bowyer 1989), but the degree of increase has not been documented for western redcedar. No references were found addressing the effect of spacing on number of branches per unit of stem length in western redcedar.

Stem taper affects lumber yields; highly tapered logs yield less lumber than more cylindrical logs of similar volume. In general, taper increases with wider spacing (Haygreen and Bowyer 1989), but the degree of increase has not been documented for western redcedar.

Western redcedar often has a fluted bole; fluting refers to longitudinal grooves and ridges in the bole which result from uneven radial growth. Fluting begins when radial growth slows and nearly stops at one or more locations around the circumference of the stem, while the rest of the circumference continues with normal or even accelerated radial growth. Fluting is of concern because it can lead to the formation of bark seams as adjacent ridges grow together, trapping the bark between them. Bark seams are a problem for either peeling or sawing of the log, and are classified as a defect in poles. Fluting can also reduce recovery even where bark seams do not occur. Oliver et al. (1988) suggest that fluting in redcedar may be more pronounced at wider spacings.

The objectives of this study were to evaluate branch size and number, fluting, and taper on the first 5m log of western redcedar trees grown at different spacings. Each of these characteristics was assessed as a function of tree spacing. Stem characteristics are often related to tree diameter, so these characteristics were also examined in relationship to tree diameter.

METHODS

Study site

The study site is a 35-year-old western redcedar spacing trial on the University of British Columbia Research Forest, near Maple Ridge, British Columbia. Reukema and Smith (1987) give a complete description. Site index (SI_{100}) for western redcedar is estimated to be 40 m; corresponding 50-yr site index for Douglas-fir is about 43 m. The trial, established in the spring of 1959, includes five spacings (0.9, 1.8, 2.7, 3.7, and 4.6 meters), in a randomized complete block design with two replications. Branches had been pruned to a height of 2 meters to facilitate access. In addition, 3 trees on each plot were pruned to a height of 6 meters in 1977.

Each plot consists of 49 trees planted at a square spacing. There are no buffers; to reduce edge effects, measurements were made only on the inner 25 tree block of each plot. All spacings were measured except the 0.9 m spacing, which was excluded because heavy mortality left few trees to measure. All field measurements were made in August 1993. Fluting measurements at breast height were taken on all surviving trees on the inner 25-tree block in each plot. Other measurements, which required access to points higher on the stem, were taken on 15 trees per plot (representing the range of diameters present).

Fluting measurements (all trees)

Fluting was quantified in several ways. First, a fluting index was calculated by the equation:

$$[(C_a/C_t) - 1] * 1000$$

where C_a is the actual circumference of the stem at breast height (1.37 m) and C_t is the circumference determined by wrapping a steel tape around the stem at the same height. The multiplier of 1000 is arbitrary and is used only to make the index numbers larger and easier to work with. This formula is based on the fact that a concave region of a stem has a greater perimeter than is indicated by a tape wrapped across that portion of the stem (Matern 1956). A stem with no fluting will have a fluting index of zero, while a fluted stem will have an index greater than zero.

Both measurements of circumferences were made to the nearest millimeter. The actual circumference (C_a) was determined by wrapping filament tape around the stem, taking care to keep the tape in contact with the bole surface along the concave, fluted sections. Before the filament tape was removed, the circumference (C_t) was measured using a steel tape wrapped around the tree, at the same height as the filament tape. The filament tape was then removed and its length measured and recorded.

In addition to the fluting index, the depth (to nearest mm) of the deepest flute and the number of flutes at breast height were recorded. Depth was measured from the deepest point to a straightedge placed across the ridges bordering the flute. A flute was defined as any concavity running parallel to the stem axis.

Other measurements (15 trees per plot)

To select the subset for additional measurements, all trees on each plot were stratified by diameter into three groups. Group 1 contained trees within half a standard deviation of the plot mean diameter; Group 2 contained trees larger than the upper limit of Group 1; Group 3 contained trees smaller than the lower limit of Group 1. Five trees were selected at random from each group. This was done to ensure that trees were sampled from throughout the diameter distribution on each plot. Any exceedingly large or small trees (outliers) and any forked trees were excluded from selection. The 3 trees on each plot that had been pruned to 6 m were also excluded from selection. On three of the plots, less than 15 acceptable trees were available, so 14 trees were measured on two plots, and 13 trees were measured on the third plot. Climbing ladders were used to collect these data.

Branch Size and Number

Branch size at each spacing was evaluated using a branch size index, which is the average of the largest branch in each quadrant of the bottom 5 m log (Bier 1986). Branch diameter was measured just far enough from the bole to avoid the branch collar (usually 3-5 cm from the bole). Measurements were made to the nearest millimeter using plastic calipers. Number of branches (branches larger than 3 mm in diameter) was counted along a 1.5 m section of the bole (3.5 to 5 m).

Taper

Stem diameter outside bark was measured to the nearest millimeter at 0.3 m (stump height) and 5.27 m (top of first 5 m log) using a steel diameter tape. Diameter at breast height (1.37 m) was calculated from the circumference measured with a steel tape during fluting measurements. Taper in the lower log was quantified using two ratios: form quotient (Husch et al. 1982) and butt swell ratio. These were calculated by the following equations:

Form quotient = $D_{5.27}/D_{1.37}$ Butt Swell Ratio = $D_{1.37}/D_{0.3}$

Highest Point of Fluting

The highest point on the stem where fluting could be observed was recorded to the nearest .05 m.

Data analysis

Stem characteristics were analyzed as a function of spacing using linear regression. Branch size index, form quotient and fluting index were also analyzed as a function of tree diameter using linear regression. In addition, comparison of regression lines was used to determine if the relationships of these characteristics to stem diameter differed between spacings (Weisberg 1985).

RESULTS

Effects of spacing

Branch Size and Number

Average branch size index increased from 15 mm to 25 mm as spacing increased from 1.8 m to 4.6 m (Figure 2.1a). The number of branches per unit of bole surface was unaffected by spacing (Figure 2.1b), and averaged about 9.5 branches per meter of bole length.

Taper

Trees at wider spacings had lower average form quotients and butt swell ratios than trees at narrower spacings (Figures 2.1c,2.1d), meaning that taper and butt swell were greater at wider spacings.

Fluting

Wider spacings tended to have more fluted trees than closer spacings (Figure 2.2), and the trees with the highest fluting indices (most severe fluting) were found at the wider spacings (Figure 2.1e). The higher fluting indices could be attributed to trees that had deeper flutes (Figure 2.1f) as well as more flutes (Figure 2.2) at breast height. At wider spacings, fluting also extended higher along the bole (Figure 2.1g). However, even at the 4.6 m spacing, there were many trees that showed no evidence of fluting at breast height (Figure 2.2). Additionally, most of the trees that were fluted had only minor fluting.

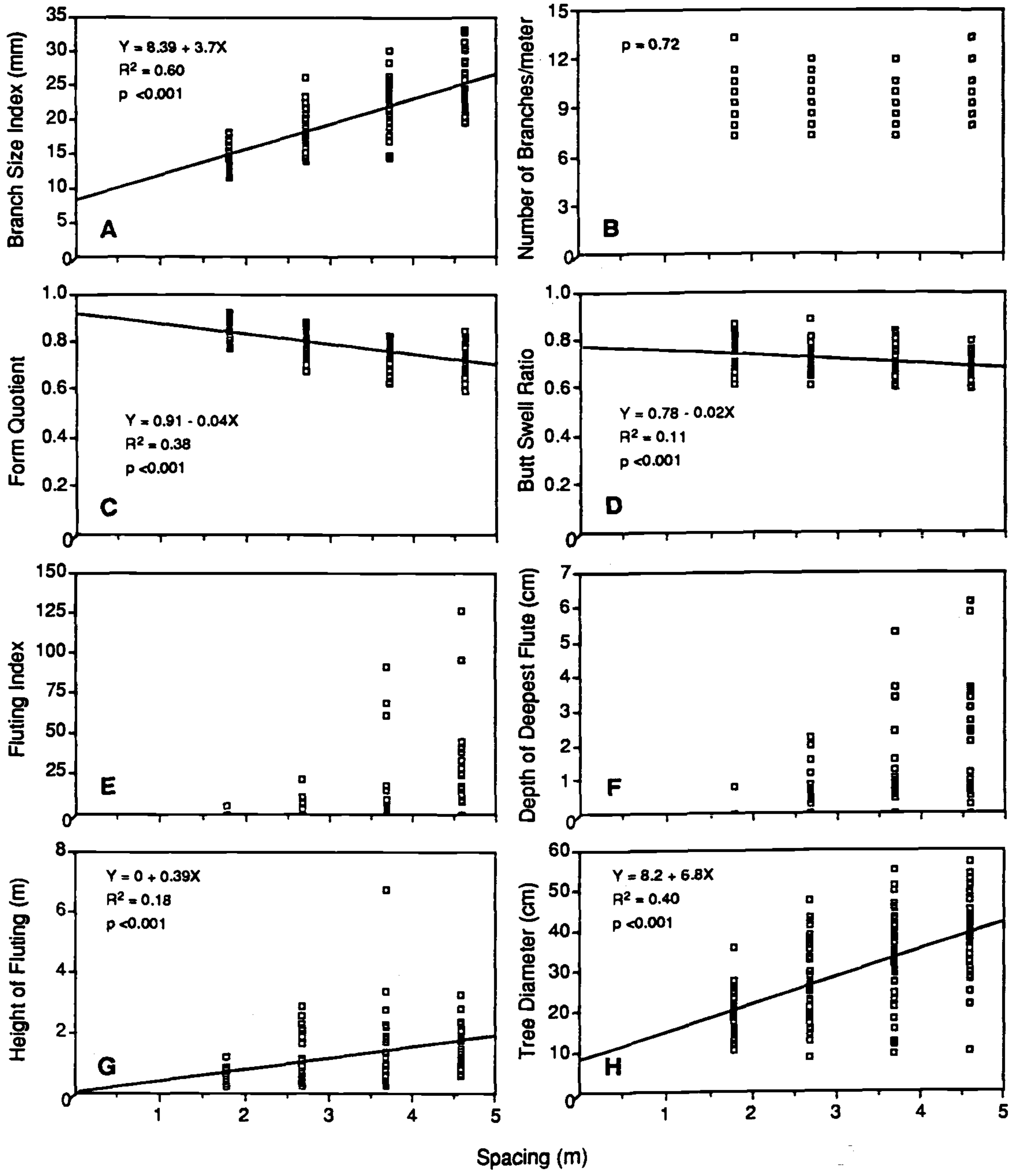

Figure 2.1. (A) Branch Size Index, (B) Number of Branches/meter, (C) Form Quotient, (D) Butt Swell Ratio, (E) Fluting Index, (F) Depth of Deepest Flute, (G) Height of Fluting, and (H) Tree Diameter vs. Spacing.

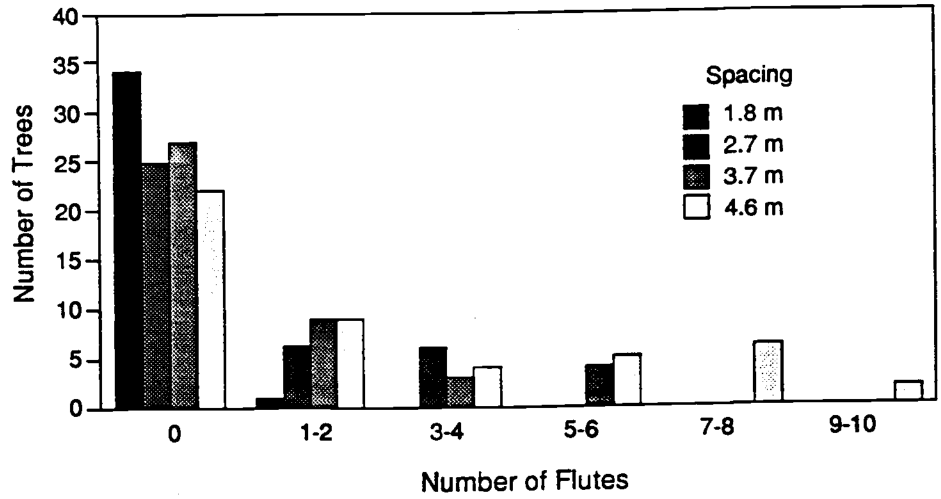

Figure 2.2. Number of fluted trees, by number of flutes per tree, for spacings of 1.8 m to 4.6 m.

Relationship to tree diameter

There was wide variation in tree diameter within each spacing (Figure 2.1h), resulting in considerable overlap in diameter distributions between the spacings.

Branch size index increased with tree diameter (Figure 2.3a). Comparison of the regression lines of each spacing indicated that slopes were not different between spacings. However, intercepts of both the 1.8m and 4.6m spacings were different from all others; there was not a significant difference in intercept between the 2.7m and 3.7m spacings (α=.05; Figure 2.3b). Comparing all four regression lines, wider spacings tended to produce larger branches even for trees of the same diameter.

Larger fluting indices were associated with larger diameter trees; trees less than about 40 cm dbh showed only minor fluting (Figure 2.3c). For trees larger than 40 cm dbh, there was wide variation in fluting index and some trees were severely fluted. However, many of the large trees had either no fluting or minor fluting.

Form quotient decreased with tree diameter (Figure 2.3d), meaning that larger trees had more taper. Comparison of the regression lines for each spacing indicated that there were no differences in either slope or intercept between spacings (α=.05).

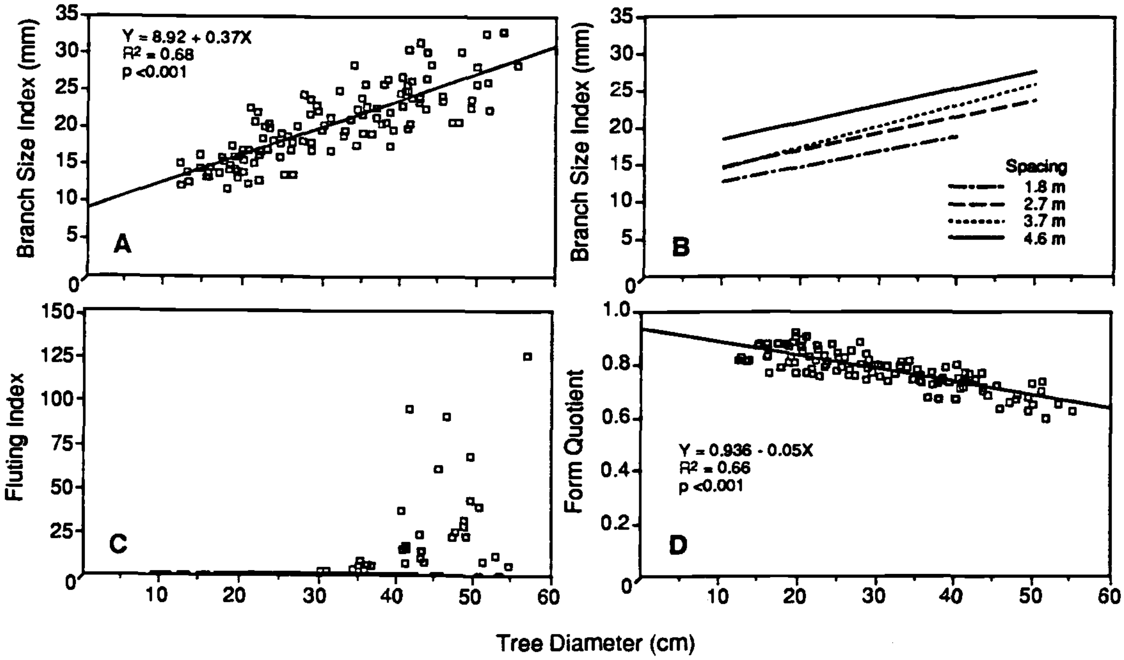

Figure 2.3. (A) Branch Size Index, (B) Branch Size Index, (C) Fluting Index, and (D) Form Quotient vs. Tree Diameter.

DISCUSSION

Effects of spacing

Branch Size and Number

Although branch diameter did increase with spacing, it remained relatively small even at the 4.6 m spacing. In fact, the largest individual branch measured was only 38 mm in diameter. Nearly all the branches measured were already dead, and the few still alive appeared to be of low vigor, so these branch diameters represent the largest size likely to be attained at these spacings even at older ages.

Branch diameter should not be an important factor in determining log grades at any of the spacings studied. At present, most logs would be classified as No. 3 Sawmill for two reasons: 1) small end diameters are less than the 51 cm required for No. 2 Sawmill, and 2) the number of branches on these logs will not allow clear cuttings of 24" lengthwise and 10" crosswise, as required by the No. 2 Sawmill grade (NLRAG 1982). As these stands grow older, more of the logs will reach the 51 cm diameter, especially at the wider spacings. However, we do not expect the clear cuttings required by the No. 2 Sawmill grade to exist at any spacing until the trees are much older than the 40-60 year rotation ages commonly used in commercial forestry operations in the Pacific Northwest. Time must be allowed for branches to break off and clear wood to be produced over the branch stubs. Therefore, it appears to us that unless rotation ages are lengthened significantly, the highest log grade likely to be achieved is No. 3 Sawmill. The only way that we would expect higher grades to be produced at conventional rotation ages is by pruning to get the required clear cuttings.

The observed differences in knot size should not cause large differences in end product grades between the various spacings. Clear or higher grade products, such as select and finish lumber, clear siding, and better grades of shakes and shingles, will not be produced from second-growth logs without either pruning or much longer rotations than are now commonly used. For many knotty lumber products, such as patio decking, common boards, light framing lumber, and lower grades of shakes and shingles, knots in this size range (15-30 mm) are acceptable (WWPA 1994).

The knot sizes reported here represent the maximum size in any product sawn from the log; for most products, especially those sawn from the inner parts of the log, the actual knot diameters will be smaller. In addition, the larger diameter trees in the wider spacings allow the manufacture of wider boards, in which larger knots are permitted. Thus, it does not seem likely that knot size will have a significant effect on grades of lumber sawn from trees grown at any of the spacings measured in this study.

Taper

These observations are consistent with generally accepted ideas about the relationship between spacing and taper. The reasons for the observed relationships can be summarized as follows: The width of the annual ring is usually greatest somewhere in the vicinity of the base of the live crown; it then decreases downward in the stem toward the base, where it may increase again in the area of the butt swell (Farrar 1961). When the width of the annual ring is fairly even down the bole (slow decrease in width), the tree tends to maintain a higher degree of taper. Conversely, when the annual ring is wide near the crown, but quickly becomes narrower further down the stem, the tree becomes more cylindrical.

The rate of decrease in width of the annual ring down the stem is related to crown vigor; in trees with smaller, less vigorous crowns, ring width decreases more rapidly than in those with larger, more vigorous crowns. Therefore, trees with small crowns, such as those grown at tight spacings, become more cylindrical than do larger crowned, widely spaced trees. Larson (1963) provides a detailed discussion and review of the literature on the subject of tree taper and its biological basis.

Fluting

The reason for the increasing incidence of fluting at wider spacings is unclear. Oliver et al. (1988) suggested that fluting in redcedar is related to interruption of photosynthate transport by dying branches, but provided no direct evidence to support this idea. Julin et al. (1993a) presented some evidence that branches may play a role in the development of fluting in western hemlock (Tsuga heterophylla (Raf) Sarg.). They hypothesized that lateral flow in the stem is restricted, and that dying branches block the longitudinal flow of one or more substances necessary for growth, leading to a decline in growth in a narrow strip above or below the branch. Under this hypothesis, more severe fluting might be expected in situations where the branch diameters were larger, such as at wide spacings.

Our observations of western redcedar trees do not suggest to us that the observed fluting is caused by interruption of flow by branches, for several reasons. First, a large percentage of the trees showed no fluting at breast height. If interruption of flow by dying branches were the cause, we would expect flutes to develop below most dying branches on most trees; this is not the case. Second, if flutes were initiated in the vicinity of branches, we would expect to find some developing flutes which begin at a branch, and extend only part way down the tree, with the deepest part immediately below the branch. We have never observed this. Every flute that we have observed extends all the way to the ground, and is deepest near the base of the tree. Julin et al. (1993a) report that in western hemlock, fluting is also deepest at the base of the tree and becomes shallower with increasing height.

This suggests our third objection, that flutes seem to be initiated at the base of the tree, not higher on the stem. In fact, all trees observed in this study showed some evidence of fluting (or minor buttressing) in the vicinity of the root collar. We suspect that this is not normally noticed and referred to as fluting. It is usually only when the regions of differential growth extend higher up the tree that they are referred to as flutes. Regardless of the vertical extent, the phenomenon appears to be the same.

With wider spacings, the fluting extended higher along the stem, so more trees were fluted at breast height. More severe fluting was associated with larger diameter trees. Julin et al. (1993b) also reported that fluting severity increased with more dominant, rapidly growing trees. A possible reason for this is that with slower growing trees, less opportunity exists for great disparities in radial growth rate between the flutes and the ridges bordering the flutes.

The observations that fluting tends to increase with tree vigor may help to explain differences in fluting between spacings, but they do not provide an explanation of the mechanism that causes the fluting in the first place. One possibility is that fluting is a structural response to mechanical stresses acting on the stem. Our observations, as well as those of Julin et al. (1993a) and Day (1964), indicate that flutes are aligned with the spaces between the junctions of adjacent roots, while the ridges bordering flutes are aligned with major roots. Day (1964) further suggests that fluting severity is influenced by the number of main roots that join the stem base, which is affected in turn by the character of the rooting medium. Fluting would be more severe when there are a few main roots than when there are many roots evenly distributed around the full circumference of the stem. Julin (1988) found that fluting in western hemlock was associated with coastal sites with western exposures, and suggested that mechanical stress from wind might play a role. Within a stand, he found that the proportion of fluted stems decreased with distance from the shore; eventually the only fluted trees were scattered individuals growing on old decomposing root wads, which are presumably less stable than soil. In the cedar spacing trial, we observed that some of the most severely fluted trees were growing on or adjacent to decaying wood left from the previous stand.

Whatever the cause, it is apparent that some degree of fluting can be expected even when redcedar is grown in pure, even-aged plantations. It is difficult to assess the importance of this fluting to wood quality, but it does not appear to be a major problem up to age 35 in the stands that we studied. The vast majority of the fluting was shallow enough to be removed with the first slab when the log is sawn. And fluting was restricted in most cases to the first 2 meters of the bottom log.

It is difficult to predict the change in fluting severity as the trees age. In most cases, we do not expect existing flutes to recover. So any existing fluting will likely develop into bark seams as the trees grow in diameter. This means that for the lower part of the first log, additional growth may be difficult to utilize. The most critical question is probably how much higher up the bole the fluting will extend with time, and whether the unfluted stems will develop fluting.

One approach to minimize fluting would be to grow trees slowly at very close spacings. But this results in smaller diameter trees at any given age, which could mean a larger loss of value than having larger stems with moderate fluting. Fluting might also be minimized by removing heavily fluted trees in thinning operations. This would likely require removal of some dominant trees in favor of codominants, but should be effective unless thinning response causes increased fluting in the residual stand.

Lacking better knowledge of the long-term development and value implications of fluting, a reasonable approach is to manage stand density to maximize volume and value as defined by existing log grades. In the second-growth cedar currently being harvested, our observation is that fluting is confined in most cases to a relatively short portion of the lower bole. Presumably, density regimes appropriate for maximizing timber production would result in a reasonable balance between fluting, growth rate and log diameter.

Relationship to tree diameter

At a given age, stem quality characteristics are often related to tree diameter. We found that larger diameter trees tend to have larger branches, more fluting, and are more tapered. These relationships have implications for managing western redcedar stands for quality wood. Regardless of spacing, larger diameter trees tended to have larger branches, more taper, and were more likely to be fluted. This information is useful in situations where trees are selectively removed from the stand, such as in a thinning operation. For instance, a forester interested in growing high quality logs might want to remove some of the larger dominant trees in a thinning, leaving more of the codominants which tend to have smaller branch diameters and less taper.

Chapter 3: Tropolone Content of Increment Cores as an Indicator of Decay Resistance in Western Redcedar

Jeffrey D. DeBell, Jeffrey J. Morrell and Barbara L. Gartner

Published in Wood and Fiber Science. 1997. 29(4):364-369.

ABSTRACT

The high decay resistance of western redcedar (Thuja plicata Donn) is due to the presence of toxic extractives, called tropolones, in the heartwood. Therefore, tropolone content may be used as an indicator of decay resistance. With increment core-sized samples of western redcedar heartwood, we used gas chromatography to measure tropolone content, and soil block tests to assess decay resistance. Results showed that decay resistance was extremely variable at low tropolone levels, but was uniformly high at tropolone levels of 0.25% or greater. Analyzing tropolone content of western redcedar increment cores is a useful way to assess decay resistance of standing trees.

INTRODUCTION

Western redcedar (Thuja plicata Donn) is a valuable commercial species in the northwestern United States and Canada. One of its most important characteristics is high decay resistance, which is due to the presence of toxic extractives in the heartwood. While a number of heartwood extractives have been shown to be toxic to fungi, the tropolones are the most important; they are comparable to pentachlorophenol in toxicity (Barton and MacDonald 1971; Rennerfelt 1948; Rudman 1962,1963). Five tropolones have been identified in western redcedar. Of these, β-thujaplicin, γ-thujaplicin, and β-thujaplicinol are the most important in terms of quantity, together making up 98% of the total tropolone content (Barton and MacDonald 1971; Frazier 1987).

Since tropolones are primarily responsible for the decay resistance of western redcedar, it should be possible to use tropolone content of the wood as an indicator of decay resistance. Tropolone content can be assessed in days; the standard method of assessing decay resistance is the soil block test, which takes 12-16 weeks. Nault (1988) noted that measurement of tropolones using gas chromatography can be accomplished with very small samples, making it possible to use increment cores to assess tropolone content of standing trees. This would be particularly useful for studying tropolone content in situations where destructive sampling is undesirable.

Techniques have been developed previously for measuring thujaplicin content using gas chromatography (Johnson and Cserjesi 1975,1980; Nault 1987,1988). The first step is extraction in a soxhlet apparatus; thus, the number of samples that can be processed at one time is limited by the number of soxhlet setups available. For some studies, it would be desirable to use an extraction method that allows more efficient processing of large numbers of samples.

We modified the technique of Johnson and Cserjesi (1980) to allow efficient handling of large numbers of increment cores or similar sized samples. We then used the technique on small samples collected from various positions within the heartwood of western redcedar trees. This paper is limited to an examination of the technique, including its repeatability and the relationship between tropolone content and decay resistance; variation of tropolone content and decay resistance as a function of position in the stem will be discussed in another paper.

METHODS

Collection of wood samples

Material for this study came from western redcedar trees growing near Clatskanie, Oregon, on the Oregon State University College of Forestry's Blodgett Tract. Eleven trees were felled (Table 3.1), and disks were cut every 2m from breast height (1.37m) to the top of the tree. The disks were taken to the lab, where they were air dried. A drill equipped with a 9.5mm plug cutter was used to remove two plugs, parallel to the stem

Table 3.1. Selected characteristics of sample trees, Clatskanie, OR.

Tree	Total Height (m)	BH Age	Crown Length (m)	DBH (cm)
A	36.2	91	13.0	52.6
B	39.3	*	26.0	87.0
C	34.6	*	15.5	67.6
D	35.2	*	15.5	68.8
E	33.8	95	15.0	47.8
F	30.8	93	12.0	33.4
G	34.8	*	16.5	57.3
H	32.4	92	15.0	50.2
I	28.7	*	13.5	43.2
J	36.0	94	16.5	62.6
K	30.8	*	13.5	67.2

* breast-height disk was decayed in center, so accurate ring count was not possible

axis and oriented side by side tangentially, from the outermost heartwood of each disk. A second pair of plugs was removed approximately 1.5 cm from the pith. One of the plugs from each pair was used for tropolone analysis, while the other was used in the decay tests. We selected the plug size because it is close to the diameter of the 8 mm increment cores we often use in wood quality studies.

Tropolone analysis

We modified the extraction technique of Johnson and Cserjesi (1980) by replacing soxhlet extraction with cold extraction in centrifuge tubes. The benefit of this modification was the ability to process larger numbers of samples quickly. The disadvantage was that complete extraction was not possible. Thus, the method is suitable for studying relative differences in tropolone content between wood samples rather than absolute tropolone content of a sample. Based on a few comparisons we made, cold extraction is capable of extracting 90% or more of the tropolones extracted by the soxhlet method.

Each redcedar plug was cut into pieces and ground in a small Wiley mill to pass through a 30-mesh screen. Approximately 0.5 g (+/- 0.01 g) of wood meal from each sample was weighed and placed in a 50 ml plastic centrifuge tube, along with 9 ml of acetone and 1 ml of an internal standard solution (3,4,5-trimethoxyphenol in acetone, about 0.35 mg/ml). The tube was capped and allowed to sit overnight (16 hours) at room temperature (23-25°C). The sample was then centrifuged for 5 minutes, and the extract was transferred by Pasteur pipet to a clean 50 ml plastic centrifuge tube.

The samples were evaporated to 1 ml by blowing air through a small hose into the tube. The sample was then transferred to a small glass vial, and evaporated to dryness using air as described above. When the sample was dry, 0.2 ml of B.S.A. (N,O-bis (trimethylsilyl) acetamide) was added, and the sample was placed in a warming tray at 70°C for 10 minutes. A needle and syringe were then used to transfer the solution to an autosampler vial, which was capped and placed in the autosampler tray to await injection into the gas chromatograph. One-microliter injections were made.

A Hewlett Packard HP-5890 gas chromatograph equipped with a flame ionization detector and an autosampler was used for analyses. The column was a Supelco SPB-5 (30m x 0.75mm). Hydrogen was the carrier gas, with a flow rate of 15 ml/min. The initial oven temperature of 125°C was held for 4 minutes, then raised at 5°C /minute to 200°C. Injector and detector temperatures were 250°C. Retention times for the internal standard and tropolones were as follows (Figure 3.1): 3,4,5-trimethoxyphenol: 9.9 min; β-thujaplicin: 10.4 min; γ-thujaplicin: 11.0 min; β-thujaplicinol: 14.6 min.

Tropolone content was determined by comparison of tropolone peak areas with that of the internal standard. Pure samples of γ-thujaplicin and β-thujaplicinol were provided by Forintek Canada Corporation. β-thujaplicin was purchased under the name Hinokitiol from a commercial supplier (TCI America). Tropolone content was expressed as a percentage of air-dried wood weight.

Small-scale analyses

In addition to analyzing tropolone content in the samples described above, we ran two small scale tests to check the precision of the method, and to assess the variation in tropolone level around the circumference of a western redcedar tree. The precision of the method was checked by separately analyzing 5 subsamples of a single bulk sample of ground cedar heartwood. The variation in tropolone content around an individual stem was assessed by analyzing 16 plugs from a single disk, as shown in Figure 3.2.

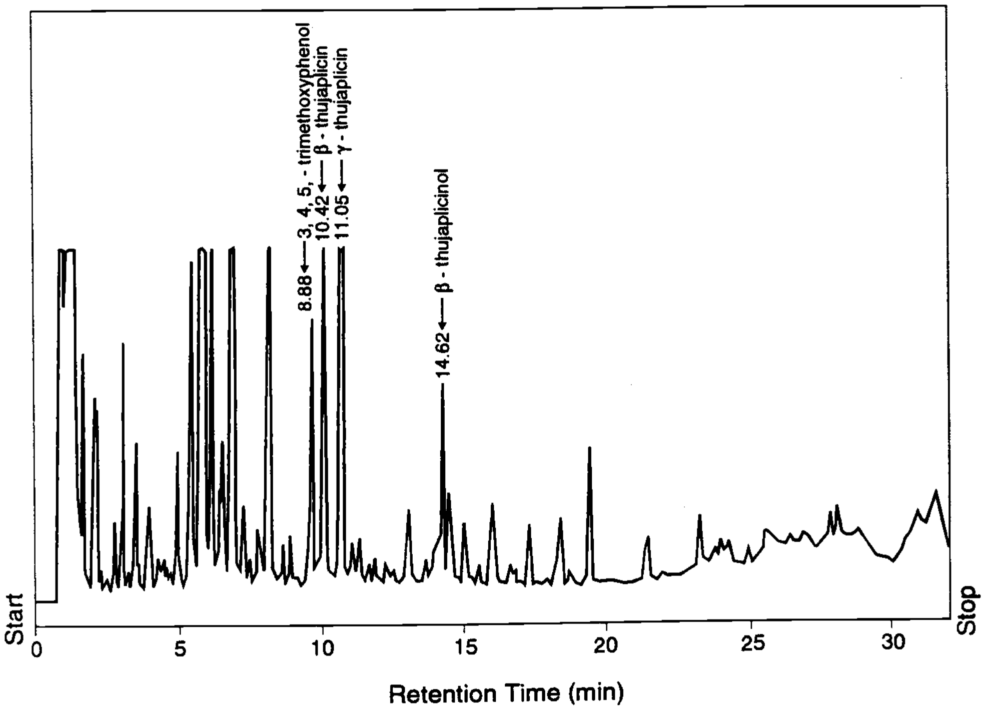

Figure 3.1. Typical chromatogram showing retention times for 3,4,5-trimethoxyphenol, β-thujaplicin, γ-thujaplicin, and β-thujaplicinol.

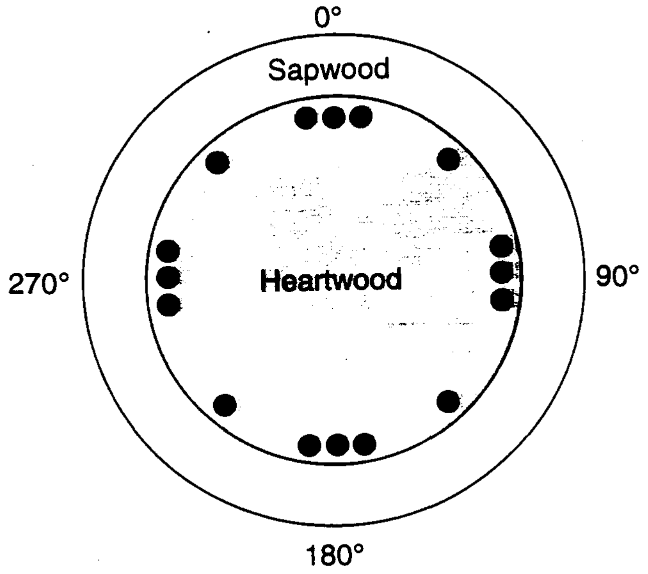

Figure 3.2. Positions of samples removed from a western redcedar disk to assess variation in tropolone content around the circumference of the stem.

Soil block tests

Soil block tests were performed using procedures described by Scheffer et al. (1987). Briefly, 113 ml glass bottles were half-filled with moist forest loam and a single 15x15x3 mm thick western hemlock (Tsuga heterophylla (Raf.) Sarg.) feeder strip was placed on the soil surface. Water was added to raise the moisture content to 100% (weight basis), then the jars were loosely capped prior to autoclaving for 45 minutes at 121°C. After cooling, the feeder strips were inoculated with 3mm diameter disks of agar cut from the actively growing edge of cultures of Postia placenta (Fr.) M. Larson & Lombard, a fungus which causes brown rot of many coniferous species. The bottles were incubated at 28°C until the feeder strips were throughly colonized by the test fungus. The cedar heartwood plugs were oven dried (54°C), weighed, and sealed in plastic bags and subjected to 2.5 Mrads of ionizing radiation from a cobalt 60 source. The plugs were placed on the feeder strips (1 plug/bottle) and the jars were then incubated at 28°C for 16 weeks. The plugs were removed, scraped clean of adhering mycelium prior to oven drying (54°C), and weighed. Loss in oven dried weight was used as the measure of decay resistance (samples with the least weight loss were considered the most decay resistant).

RESULTS AND DISCUSSION

Small-scale analyses

The coefficient of variation for tropolone content of the five subsamples from a single batch of cedar meal was 4.5%. This low level of variation indicates that the modified method gives consistent results; we consider this level of precision to be acceptable for wood quality studies.

Tropolone content around the outer heartwood was fairly uniform around most of the disk, averaging between 0.2 and 0.3% (Figure 3.3). But samples from the 180 degree position contained nearly double the troplone content of samples from the rest of the disk. There was no obvious reason for the higher level at this position. From these data, it appears that a single increment core should be a useful indicator of tropolone content at a given location in a tree. With a single core, the tropolone content of some trees could be significantly over- or underestimated if an increment core includes an atypical zone like the one we encountered at the 180 degree position (Figure 3.3). If only a few trees are sampled, average tropolone content at the sampling height could be also be over- or underestimated. In this case, one might want to get several samples per tree to improve the reliability of the estimate for each tree. However, if the sample size (number of trees) is large enough, the effect of hitting an atypical zone in a few trees should be unimportant to the overall results, and the extra work of collecting multiple cores from each tree may not be justified.

The consistency in tropolone content at positions where clusters of three samples were taken increased our confidence in the precision of the method (Figure 3.3). The data also suggested that if multiple increment cores are taken from a single tree, the cores should be separated by at least 90 degrees, since taking two cores near the same point may do little to improve the estimate of the average troplone content at that height in the tree.

Relationship of tropolone measurements to soil block tests

Tropolone content of the wood samples ranged from 0 to 1.2% (weight basis), while weight loss ranged from 0 to 70% (Figure 3.4). Weight loss was highly variable for samples with tropolone content <0.10%, but averaged 21% loss. Weight loss was less variable for samples with tropolone contents between 0.10% and 0.24%, averaging 9% loss. Samples with tropolone content $\geq$0.25% had consistently low weight loss; average

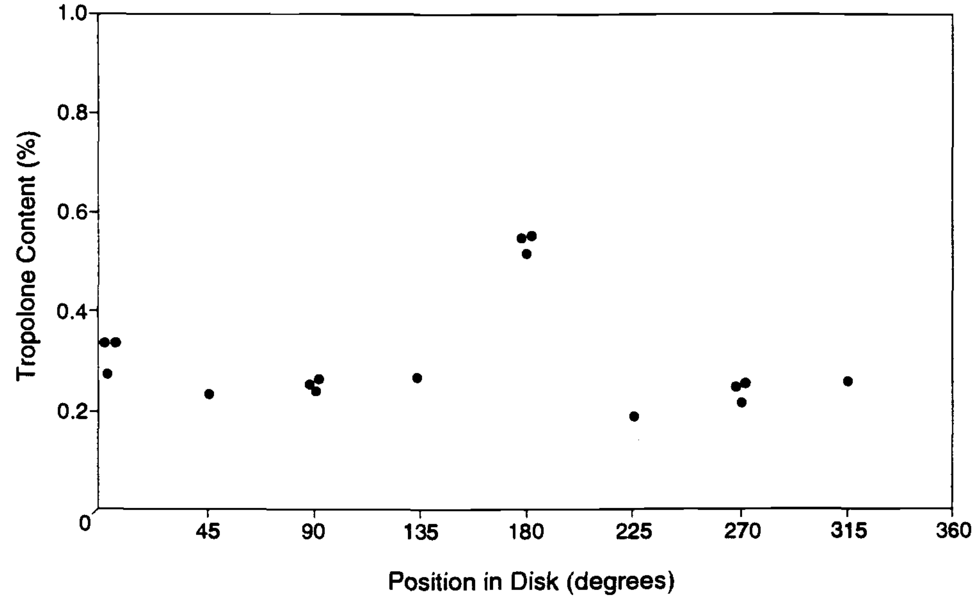

Figure 3.3. Variation in heartwood tropolone content around the circumference of a western redcedar stem.

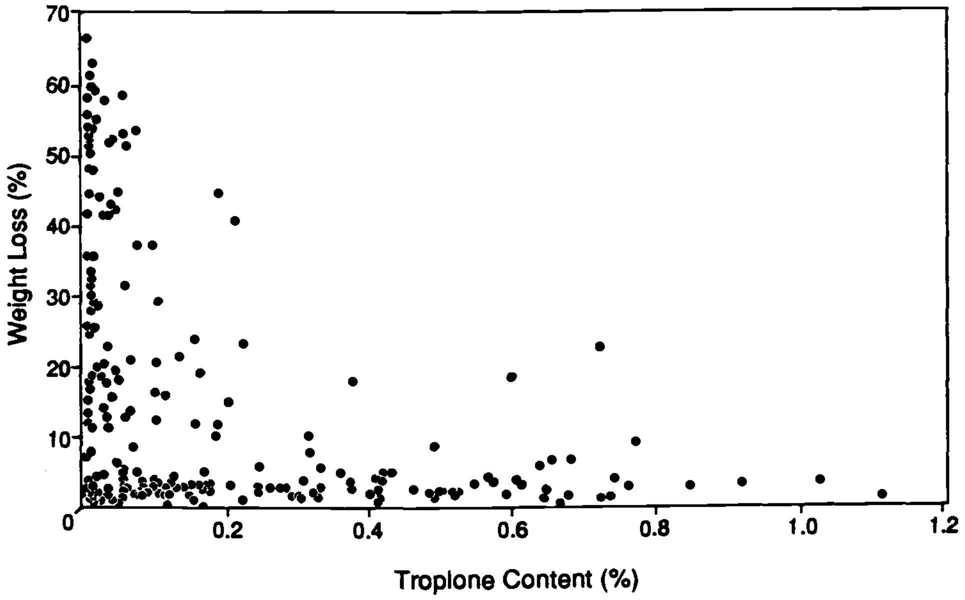

Figure 3.4. Relationship between tropolone content and weight loss in soil block tests for paired samples of western redcedar heartwood.

weight loss was 4%. Only 3 out of the 59 samples with high tropolone content had more than 10% weight loss.

We are unsure of the reasons for the high variability in weight loss in samples with low tropolone levels. One possibility is that other substances in the heartwood prevented significant decay in some samples. However, there were no obvious patterns in the chromatograms to suggest any major differences in other extractives between low tropolone samples. Differences in tropolone distribution could influence the results, since the extract and decay samples were separate but adjacent plugs; however, the results from repeated sampling of a single disk (Figure 3.3) suggest that these differences should be minimal. The variability of the soil block test may be a factor, since individual decay tests can sometimes vary widely.

These results indicate that tropolone analysis of increment cores is a useful way to assess decay resistance at a given position in standing trees. The modified analysis method, using cold extraction, gave consistent results and could be used with large numbers of samples efficiently. This technique should be particularly useful for wood quality studies, where many trees must be sampled.

Chapter 4: Within-Stem Variation in Tropolone Content and Decay Resistance of Second-Growth Western Redcedar

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Submitted to Forest Science

ABSTRACT

Western redcedar (Thuja plicata Donn) is a commercial species valued for its high decay resistance, which is due to the presence of toxic extractives (tropolones) in the heartwood. We measured tropolone content and weight loss in soil block tests using samples taken from throughout eleven second-growth western redcedar trees. Tropolone content increased with rings from the pith, and in the outer heartwood, increased from the top to the base of the tree. We did not find any consistent increase or decrease in tropolone content with height in the tree for samples the same number of rings from the pith. Our data suggest that the lower tropolone content near the pith is largely a juvenile effect, associated with wood formed near the active crown. This has implications for choosing a rotation length if wood of uniformly high decay resistance is desired, because younger trees contain a greater proportion of wood close to the pith. However, we also found large tree-to-tree differences in the rate of tropolone increase with age from the pith. This may have promise for maintaining uniformly high decay resistance if the factors underlying the tree-to-tree differences can be discovered and managed. Our results from soil block tests for decay resistance were more variable, but in general, wood with low tropolone content (<0.1%) was extremely variable in decay resistance, while wood with high tropolone content (>0.3%) showed higher, less variable decay resistance.

INTRODUCTION

Western redcedar (Thuja plicata Donn.) is a valuable commercial species in the northwestern United States and southwestern Canada. One of western redcedar's most important wood characteristics is its resistance to decay, which is due to the presence of toxic extractives in the heartwood. Although several of the heartwood extractives have been shown to be toxic to fungi, the tropolones are the most important source of the decay resistance, and are reported to be comparable to pentachlorophenol in toxicity (Barton and MacDonald 1971; Rennerfelt 1948; Rudman 1962,1963). Five tropolones have been identified in western redcedar. Of these, β-thujaplicin, γ-thujaplicin and β-thujaplicinol are the most important in terms of quantity, together making up about 98% by weight of the total tropolone content (Barton and MacDonald 1971; Frazier 1987).

Historically, most western redcedar products have been produced from old-growth trees. However, with the declining availability of old-growth redcedar (especially in the U.S.), future redcedar products will be made from second-growth trees. Several studies have indicated that the concentration of tropolones, and thus presumably decay resistance, is lower in second-growth wood compared to wood from old-growth trees (MacLean and Gardner 1956; Swan and Jiang 1970; Nault 1988). The difference seems to be related to tree age, but the specific reasons behind the observed variation are not entirely clear. In this paper, we review existing information about variation of tropolones and decay resistance within western redcedar trees, and describe results from further studies that attempt to clarify the causes of the previously observed patterns.

Observed within-tree variation in extractive content and decay resistance

Most researchers who have studied within-tree variation in tropolone/extractive content or decay resistance in western redcedar report an increase in decay resistance and tropolone/extractive content from the pith outward at a given height (Cartwright 1941; Englerth and Scheffer 1955; MacLean and Gardner 1956; Scheffer 1957; Nault 1988). With respect to height in the tree, results have been more variable. Most studies found the highest levels of extractives and decay resistance in the outer heartwood at the base of the tree. Above that, results for extractives have not been consistent. Decay resistance has generally been found to decrease with height in the tree. However, in some of the studies, it appears that height differences were confounded with differences in age from the pith. Given the known radial variation in extractive content and decay resistance, it is difficult to be certain that the observed differences were truly related to height itself rather than distance from the pith.

Causes of variation in extractive content

The possible causes of variation in extractive content or decay resistance with height in the tree have received little attention in the literature. In contrast, several authors have discussed possible reasons for variation in the radial direction at a given height, so we review that here. The reported change in extractive content with distance from pith could be due either to: i) a change with tree age or rings from the pith in the amount of extractives formed at the sapwood/heartwood boundary or ii) a degradation of previously formed extractives over time (Hillis 1987).

Some studies suggest that tropolone degradation over time produces the observed patterns in tropolone content and decay resistance. Scheffer (1957) studied decay resistance of freshly cut redcedar poles vs. poles which had been in use for 20-30 years, and suggested that natural preservatives slowly undergo a chemical modification that reduces their toxicity. In more recent work, it has been demonstrated that certain fungi found in western redcedar heartwood are capable of degrading thujaplicins into less toxic compounds (van der Kamp 1986; Jin et al. 1988).

Other studies suggest the first possibility, a change with age in the amount of extractives formed at the sapwood/heartwood boundary. Swan and Jiang (1970) reported that the thujaplicins were not formed in the heartwood of very young trees. Also, extractive content in the outer heartwood of second-growth trees was found to be lower than that of old-growth trees (MacLean and Gardner 1956; Nault 1988). It is not entirely clear whether extractive content at the heartwood/sapwood boundary increases with total tree age, or whether the observed pattern is a juvenile wood phenomenon, where extractive content of wood at a given height varies with age from the pith, rather than total tree age. MacLean and Gardner (1956) found that thujaplicin content in the newly formed heartwood of young trees was lower than for newly formed heartwood of mature trees; they suggested that as a tree ages, its ability to produce fungicidal extractives increases. Swan and Jiang (1970) reported that the heartwood extractive content near the top of an old tree (400 years) was similar to that found near the base of a younger tree (90 years); this suggests that extractive content at a given height varies with age from the pith rather than total tree age.

Despite these general conclusions, some uncertainty remains as to the reasons underlying the variation in tropolone content and decay resistance. Some differences in previous results may reflect the fact that most studies were based on either intensive sampling of one or two individual trees or only two to three sampling positions in a larger number of trees. Also, most previous studies have not been designed to clearly distinguish effects of age from the pith from those of height in the tree. To help clarify the causes of the observed patterns of variation in tropolone content and decay resistance, we intensively sampled eleven trees in a study of western redcedar trees from a second-growth stand.

METHODS

The trees used in this study came from a second-growth stand of western redcedar, western hemlock (Tsuga heterophylla (Raf.) Sarg.), and Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) growing near Clatskanie, Oregon, on the Blodgett Tract, owned and managed by the Oregon State University College of Forestry. Eleven western redcedar trees were felled; total height was measured, then disks were cut every 2 m from breast height (1.37m) to the top of the tree. The disks were taken to the lab, where they were air dried. Selected tree characteristics are listed in Table 4.1. Most of the trees showed some discoloration or decay at the center of the disks near the base of the tree.

Framework for studying within-tree variation

To help determine the cause of the reported within-tree variation, samples were evaluated along several transects within each tree (Figure 4.1). This approach is similar to the ring series described by Duff and Nolan (1953), but differs somewhat from that approach in that the heartwood boundary does not follow any specific annual ring.

The **radial sequence** is a set of samples from a given height in the tree (such as samples cut from a single increment core or disk), from the pith to the outer edge of the heartwood. In this sequence, all samples are from the same height in the tree, but were converted to heartwood in different years and at different distances from the active crown and the pith at the time of their formation. We examined a radial sequence at or near breast height in each tree.

The **vertical sequence** is a set of samples from different heights in the tree, but all the same distance from the pith. In this sequence, samples were converted to heartwood in different years and at different heights in the tree, but at roughly the same distance from the active crown and the pith at the time of their formation. We examined three vertical sequences, corresponding to the innermost heartwood, the 20th ring from the pith, and the 40th ring from the pith.

The **outer heartwood sequence** includes samples adjacent to the sapwood/heartwood boundary from different heights in the tree. Since the heartwood/sapwood boundary occurs progressively further from the pith with increasing

Table 4.1. Selected characteristics of sample trees, Clatskanie, Oregon.

Tree	Total Height (m)	BH Age	Crown Length (m)	DBH (cm)
A	36.2	91	13.0	52.6
B	39.3	*	26.0	87.0
C	34.6	*	15.5	67.6
D	35.2	*	15.5	68.8
E	33.8	95	15.0	47.8
F	30.8	93	12.0	33.4
G	34.8	*	16.5	57.3
H	32.4	92	15.0	50.2
I	28.7	*	13.5	43.2
J	36.0	94	16.5	62.6
K	30.8	*	13.5	67.2

* breast-height disk was decayed in center, so accurate ring count was not possible

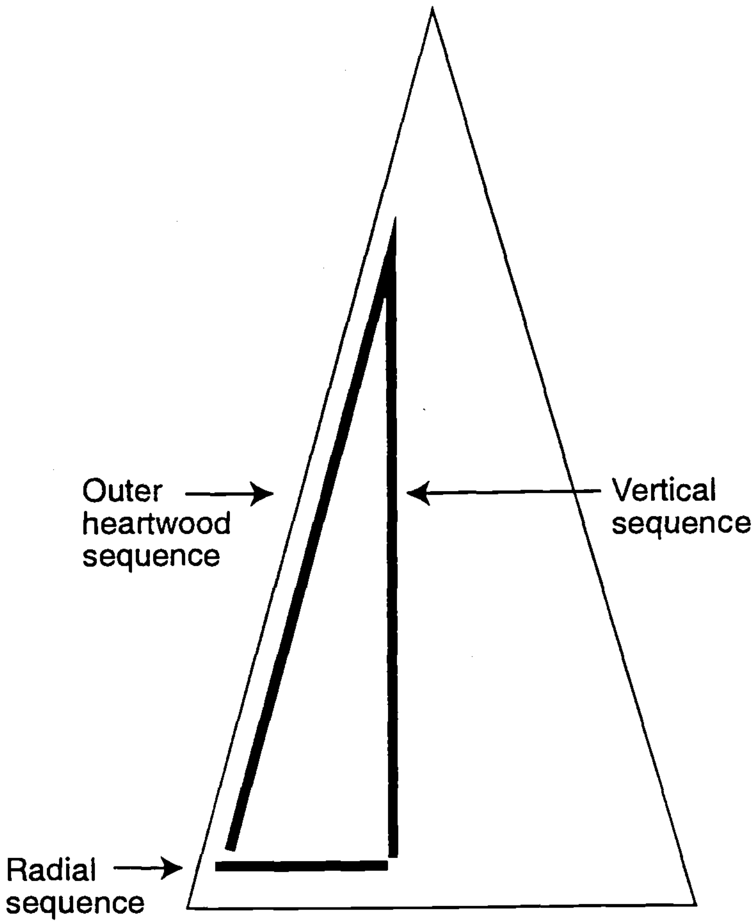

Figure 4.1. Sampling scheme for studying within-tree variation of tropolone content and decay resistance. The vertical sequence is composed of samples the same distance from the pith, but at different heights in the tree. The outer heartwood sequence contains the newest formed heartwood at different heights in the tree. The radial sequence consists of samples progressively farther from the pith at a given height in the tree.

distance from the top of the tree, it has components of both a vertical and a radial sequence. In this sequence, all samples were converted to heartwood at roughly the same time, but at different heights in the tree and at different distances from the active crown and the pith.

Both tropolone content and decay resistance were examined along the inner vertical sequence and the outer heartwood sequence. In addition, tropolone content was assessed in the breast height radial sequence, and the vertical 20 and 40 sequences. In analyzing these sequences, we express height in the tree as distance from the terminal (top of the tree) rather than height from the base. This does not change the observed patterns, but does help focus on the biological causes which are presumed to underly those patterns. Radial variation in wood characteristics of other species has been shown to vary with age from the pith rather than total tree age. This pattern has has been attributed to the changing position of the cambium relative to the active crown (Larson 1969). At any given height, rings formed near the pith were formed when the top of the tree crown was just above that point. In contrast, rings far from the pith were formed when the top of the crown was far above that point. The question is more complicated with heartwood, because heartwood is formed some years after the wood is formed at the cambium. However, the general concept is useful for heartwood studies.

Below, we discuss the predicted patterns of variation in the vertical and outer heartwood sequences for each suggested cause of the observed increase in tropolone content and decay resistance in the radial direction:

(1) If the increase in tropolone content and decay resistance in the radial direction is due primarily to degradation of tropolones over time, tropolone content should decrease with distance from the terminal in the vertical sequences and remain relatively constant in the outer heartwood sequence.

(2) If the increase in the radial direction is a juvenile wood phenomenon (varies with age from the pith), tropolone content should remain relatively constant in the vertical sequence and increase with distance from the terminal in the outer heartwood sequence.

(3) If the increase in the radial direction is due simply to total tree age, tropolone content should decrease with distance from the terminal in the vertical sequence and remain relatively constant in the outer heartwood sequence.

Note that the patterns in (1) and (3) are the same. Our sampling scheme is not capable of distinguishing between these two causes. Scenario (1) assumes that tropolone content at the heartwood/sapwood boundary is constant as the tree ages, but begins to deteriorate after formation, while (3) assumes that tropolone content at the heartwood/sapwood boundary increases uniformly throughout the tree as the tree ages. These scenarios could be distinguished by sampling the newest-formed heartwood from western redcedar trees representing a range of ages.

Extraction of wood plugs from disks

A drill equipped with a 9.5 mm plug cutter was used to remove two plugs, parallel to the stem axis and oriented side by side tangentially, from the outermost heartwood of each disk (outer heartwood sequence). A second pair of plugs was removed approximately 1.5 cm from the pith (vertical inner sequence). One of the plugs from each pair was used for tropolone analysis, while the other was used in decay tests.

In addition to the paired plugs, we took single plugs for tropolone analysis only at the 20th and 40th rings of each disk if they fell in the heartwood (vertical 20 and 40 sequences), and at every 10th ring in the breast height disks (radial sequence). In some cases, the center of the breast height disk was badly decayed, so we took the plugs for the radial sequence from the lowest disk where the inner rings could be counted. For all plugs, the number of rings from the pith was recorded.

Tropolone analysis

We used a modified version of Johnson and Cserjesi's (1980) method for tropolone analysis by gas chromatography (DeBell et al. 1997).

Decay tests

Soil block tests were performed using procedures described by Scheffer et al. (1987). Specific details are described by DeBell et al. (1997). Percent weight loss was used as the measure of decay resistance.

RESULTS

Tropolone content

Both the radial and the outer heartwood sequences showed an increase in tropolone content with rings from the pith, although both the rate of increase and maximum tropolone content varied substantially among trees (Figure 4.2). The general pattern of increase was remarkably similar in both sequences within a tree, and the radial sequence tended to have a lower tropolone content than the outer heartwood sequence. The increase in tropolone content from pith to outer heartwood is also seen in Figure 4.3;

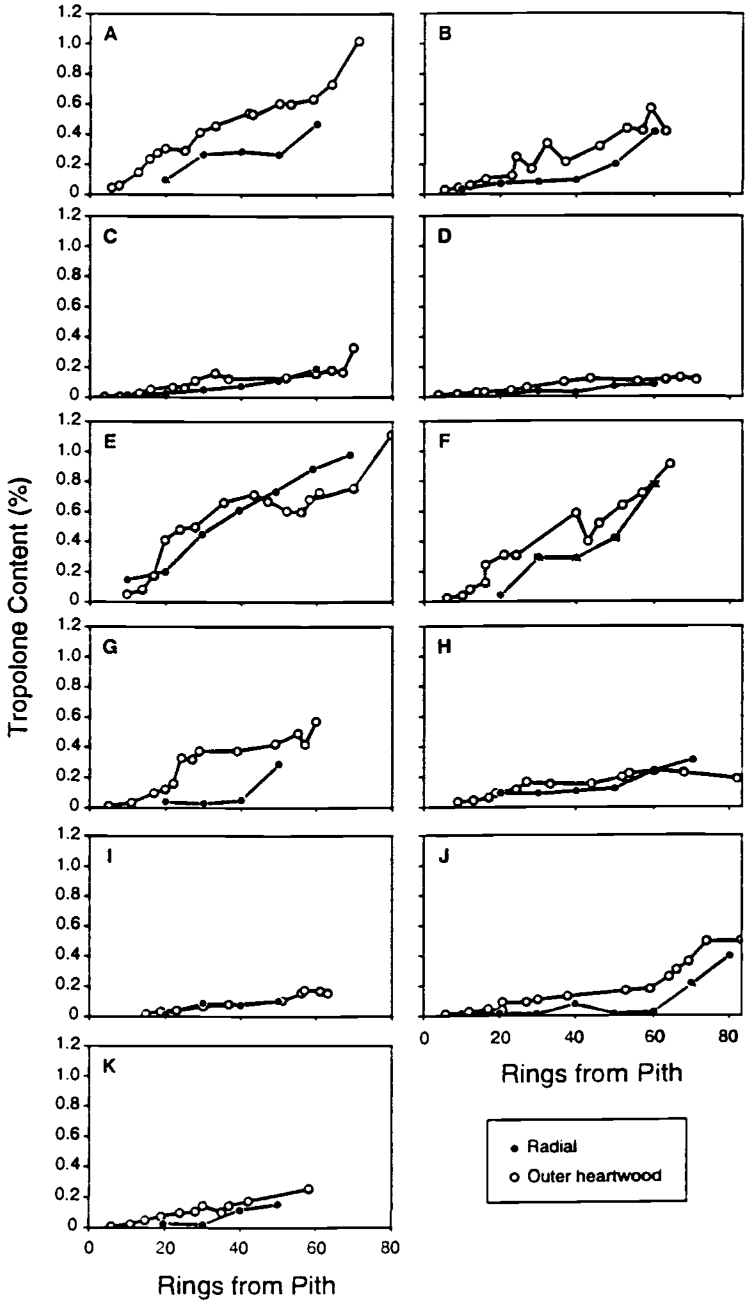

Figure 4.2. Variation of tropolone content with number of rings from the pith in the outer heartwood and radial sequences. The letter in the corner of each graph is the identifier assigned to each tree.

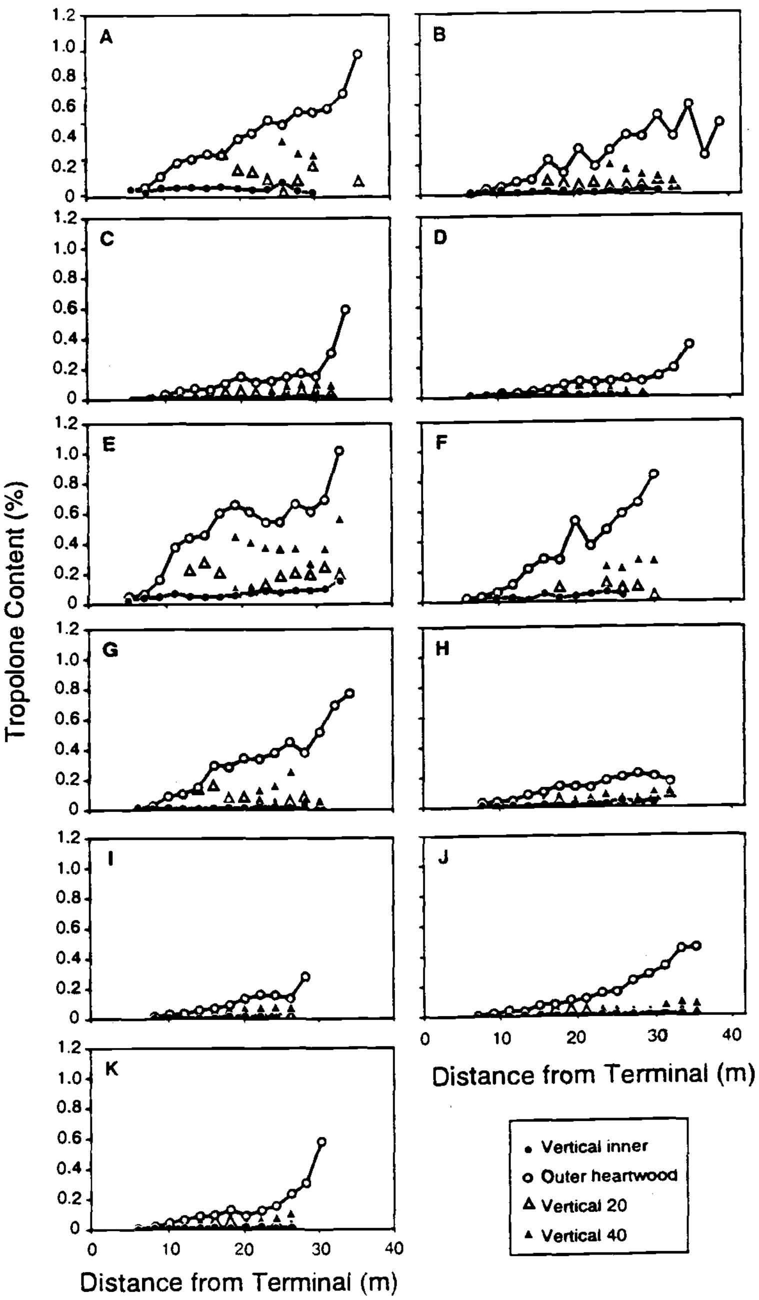

Figure 4.3. Variation of tropolone content with distance from the terminal in the outer heartwood, vertical 40, vertical 20, and vertical inner sequences. The letter in the corner of each graph is the identifier assigned to each tree.

samples from the vertical inner, vertical 20th, vertical 40th, and outer heartwood sequences were successively higher in tropolone content.

The vertical inner sequence was low in tropolone content throughout the tree, with no obvious patterns of increase or decrease (Figure 4.3). There was no consistent pattern of increase or decrease with distance from the terminal in the vertical 20th or 40th ring sequences, either, but the 40th sequence tended to have a higher tropolone content than the 20th sequence. Tropolone content in the outer heartwood sequence increased with distance from the terminal, but the rate of increase as well as maximum tropolone content varied substantially among trees.

Decay resistance

Weight loss in the vertical inner vertical sequence was quite variable throughout the tree (Figure 4.4). Weight loss in the outer heartwood sequence was generally most variable in samples near the terminal, and in some trees became lower and less variable as distance from the terminal increased. However, in other trees, weight loss in the outer heartwood remained variable even down to the base of the tree; these tended to be trees with low tropolone content throughout the outer heartwood sequence (Figure 4.3). The highest and most variable weight losses were associated with samples containing very low tropolone levels (<0.1%); samples with more tropolones experienced a lower, less variable degree of weight loss (Table 4.2). At all levels of tropolone content, the standard deviation was roughly equal to the mean for weight loss.

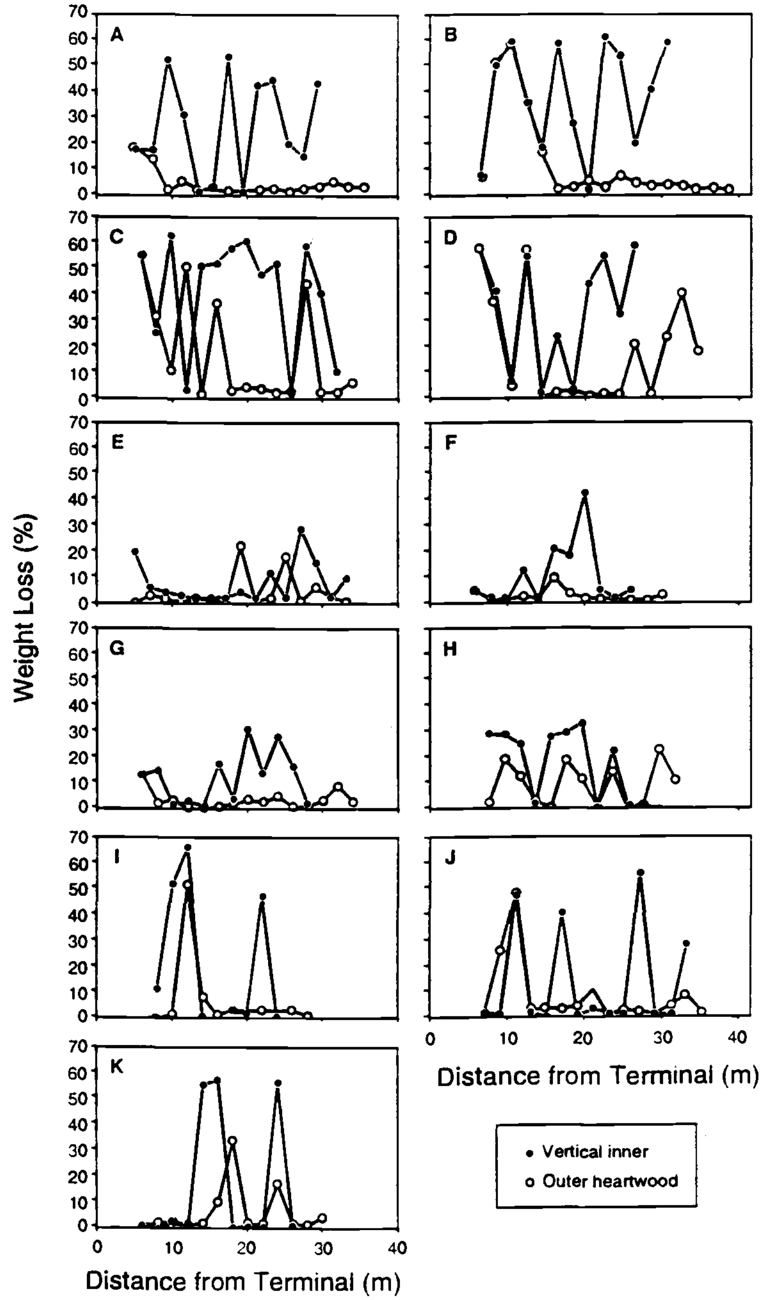

Figure 4.4. Variation in weight loss in soil block tests with distance from the terminal in the outer heartwood and vertical inner sequences. The letter in the corner of each graph is the identifier assigned to each tree.

Table 4.2. Weight loss in soil block tests by tropolone content classes.

Tropolone %	N	Weight Loss (%)	
		Mean	S.D.
< 0.1	163	21.2	21.6
0.1 - 0.2	46	8.3	9.8
0.2 - 0.3	13	8.1	11.6
0.3 - 0.4	15	4.6	4.5
0.4 - 0.5	13	3.1	2.2
0.5 - 0.6	9	4.3	5.4
> 0.6	20	4.4	4.8

DISCUSSION

Tropolone content

We found the same general pattern of increase in tropolone content from pith to outer heartwood reported by other authors (Cartwright 1941; Englerth and Scheffer 1955; MacLean and Gardner 1956; Scheffer 1957; Nault 1988). The fact that the increase with rings from the pith occured in the outer heartwood sequence as well as the radial sequence indicates that this pattern was not due simply to the breakdown of tropolones over time. The outer heartwood sequence consisted of samples formed recently and at roughly the same time. Previous work has established that newly formed outer heartwood is free of tropolone degrading fungi (Jin et al. 1988; van der Kamp 1986), so tropolone degradation is an unlikely explanation for the variation in the outer heartwood sequence. These trends also indicate that tropolone content at the heartwood/sapwood boundary did not simply increase as the trees aged, because the newly formed heartwood from the upper part of the tree was low in tropolones - similar to the innermost heartwood at the base of the tree; this is consistent with the studies of Swan and Jiang (1970). Additionally, if tropolone content simply increased with tree age, we would expect tropolone content to decrease with distance from the terminal in the vertical 20th and 40th ring sequences, because the samples further from the terminal were formed when the tree was younger. However, there was no clear pattern of increase or decrease in tropolone content in either the vertical 20th or 40th ring sequences. The pattern of radial increase in tropolone content appeared to be a juvenile wood phenomenon, due primarily to differences in the amount of tropolones created at the time of heartwood formation, which varied in response to: 1) changing distance of that height from the active crown as the tree aged or 2) changes in cambial age at that height as the tree aged. We cannot separate those two factors in our study.

While the observed pattern of radial variation in tropolones appeared to be due primarily to differences in the amount of tropolones created at the time of heartwood formation, this initial pattern can be altered by degradation of tropolones over time, as suggested by Scheffer (1957), van der Kamp (1986) and Jin et al. (1988). In fact, our data suggests that some degree of degradation occurred over time in the trees that we studied. The radial sequence, which consisted of samples formed over many years, tended to be lower in tropolone content than the outer heartwood sequence, which was formed recently. However, given the strong similarity within trees between the radial and outer heartwood sequences, it appears that tropolone degradation was less important than the amount of tropoplones originally deposited as a cause of the tropolone variation in the second-growth trees that we studied. If tropolone degradation were the most important factor, we would expect to see a clear decrease in tropolone content with increasing distance from the terminal in the vertical 20th and 40th ring sequences; rings further from the terminal would be older, allowing more time for tropolone degradation. No consistent pattern was evident in either the 20th or 40th ring sequences. While some trees showed a mild decrease with distance from terminal, others showed a mild increase; for most, there was no clear pattern.

Since the outer heartwood sequence has both a radial and a vertical component, it is not possible to separate the effects of rings from pith from those of height in the tree when the outer heartwood sequence is studied alone. However, since we also studied purely radial and purely vertical sequences, we can compare patterns in the outer heartwood sequence to the others to look for similarities. The strong similarity of pattern between the outer heartwood and radial sequences, along with the lack of pattern in the three vertical sequences, suggests that the variation in the outer heartwood sequence can be attributed primarily to its changing radial position at different heights; height itself appears to have a much smaller, if any, influence.

The large differences among trees in the rate of increase in tropolone content with rings from the pith are worth noting. The similarity within trees of these tropolone patterns in both the radial sequence and the outer heartwood sequence is remarkable (Figure 4.2), especially considering that these two sequences represent two very different sets of samples from different parts of the tree. This suggests to us that the rate of increase in tropolone content with rings from the pith is an inherent tree characteristic that is maintained over time. There were no obvious differences in environment or growth rate correlated with these differences between trees; the trees that were highest in tropolone content were neither the largest nor the smallest individuals (Table 4.1). The lack of apparent environmental differences suggests the possibility of genetic differences. But both common-garden tests and isozyme analyses suggest a very low level of genetic variation in western redcedar (El-Kassaby et al. 1994; Rehfeldt 1994). Thus, reasons for the large tree-to-tree differences in the rate of increase in tropolone content with rings from the pith remain unclear. Our results were consistent with Nault (1988), who also found large differences in tropolone content among trees from the same stand.

Decay resistance

The decay resistance data lacked the clear trends found in the tropolone data. This is probably due in part to inherent variability in soil block tests, and the fact that we ran only one sample per position in the tree, so we could not reduce the variability by averaging multiple samples for each position. In most trees, many samples from the vertical inner sequence lost 25%-60% of their weight in the soil block tests (Figure 4.4). However, other samples in the same sequence lost almost no weight. Therefore, it seems more accurate to describe the vertical inner sequence (all samples from near the pith) as having extremely variable decay resistance rather than consistently low resistance. Weight losses in the outer heartwood sequence were also variable, but less so than the inner heartwood. Samples further from the terminal, which were usually higher in tropolone content, tended to have lower and less variable weight losses than the vertical inner heartwood sequence. In some cases, however, weight losses remained quite variable throughout the outer heartwood sequence. These tended to be trees in which tropolone content remained fairly low. Despite the more variable results in within-tree patterns of weight loss data, samples with high levels of tropolone tended to experience lower and less variable weight loss than samples with low tropolone levels (Table 4.2; DeBell et al. 1997). Both the mean and the standard deviation for weight loss in samples with tropolone content of less than 0.1% were two to four times greater than for samples with higher tropolone levels. This suggests that the patterns observed in tropolones do correlate to patterns in decay resistance. We suspect that if we had used averaged values for several samples per location in the tree, the variability in weight loss data would decrease, and the patterns in decay resistance would be more clear. The generally lower decay resistance of inner heartwood is consistent with previous studies (Cartwright 1941; Englerth and Scheffer 1955; Scheffer 1957).

Relationship of tropolone content to decay resistance

Most samples with high tropolone content experienced low weight loss, but samples with low tropolone content were extremely variable in weight loss, ranging from 0% to over 60% (Table 4.2; DeBell et al. 1997). We are unsure of the reasons that weight loss was not more consistently high for low tropolone samples. van der Kamp (1986) also noted that samples with low tropolone content may not exhibit low decay resistance in tests. He suggested two possible reasons for this: 1) some unknown toxic thujaplicin derivative, created by breakdown of thujaplicins, may inhibit fungal growth, or 2) other antagonisitic microorganisms in the wood inhibit fungal growth. In support of the first possibility, Jin et al. (1988) described a compound called thujin, created by the breakdown of thujaplicins by the fungal species Kirschsteiniella thujina (Peck) Pomerleau & Etheridge. However, thujin was not toxic to Poria rivulosa (B. & C.) Cooke, the common decay fungus of coastal western redcedar. It is unlikely that antagonistic microorganisms were responsible for low weight loss in our samples, because they were exposed to radiation, which should have eliminated this source of variation.

Another possible explanation for the low weight loss in some of the low tropolone samples is inhibition of fungal growth by other compounds in the wood. Roff and Atkinson (1954) reported that western redcedar extract from which tropolones had been removed inhibited the growth of Postia placenta (Fr.) M. Larson and Lombard in malt agar, and suggested that extractives other than tropolones are partly responsible for the decay resistance of redcedar wood. We did not note any unusual patterns in the chromatograms from low tropolone, low weight loss samples, but we did not concentrate on identifying or quantifying compounds other than the tropolones in our study.

Management implications

Much of the economic value of western redcedar comes from its reputation for high decay resistance. This reputation was created by wood that came primarily from old-growth trees. Our results indicate that second-growth trees are also capable of producing wood with high tropolone content and decay resistance. However, both our data and that of other researchers suggest that there is a zone near the pith that contains a lower tropolone content than wood farther from the pith, even in newly formed heartwood where degradation of tropolones has not occurred. This is much like the pattern observed in many wood anatomical properties that has been described as "juvenile wood." Trees harvested at younger ages will contain a larger percentage of wood near the pith, and thus with lower levels of tropolones. Soil block tests suggest that while wood with low tropolone levels may not always perform poorly, performance will be highly variable. Managers should be aware of the potential importance of rotation age to maintaining high tropolone content and uniform decay resistance in future western redcedar products.

The differences between individual trees in the rate of tropolone increase with rings from the pith indicate that the impact of rotation length may differ greatly between trees. Some trees begin producing wood of high tropolone content at fairly young ages, while others continue to produce low tropolone levels even in wood 70 rings from the pith (Figure 4.2). Understanding the reasons behind these differences may make it possible to manage for high tropolone content, thereby reducing the importance of rotation age to tropolone content and decay resistance.

Chapter 5: Heartwood/Sapwood Relationships of Western Redcedar as Influenced by Cultural Treatments and Position in Tree

Jeffrey D. DeBell and Barbara L. Gartner

ABSTRACT

We studied heartwood and sapwood relationships at three sites, including an approximately 90-year-old naturally regenerated, unmanaged stand, a 35-year-old planted spacing trial, and an approximately 30-year-old naturally regenerated stand to which thinning and fertilization treatments had been applied. In the 90-year-old stand, which was in northwest Oregon, we studied within-tree variation in heartwood/sapwood relationships. In the the thinning/fertilization trial and the planted spacing trial, which were on the Olympic Peninsula in Washington and near Vancouver, British Columbia, respectively, we studied effects of cultural practices and growth rate on heartwood/sapwood relationships. In the trees that we studied, sapwood width was generally fairly narrow, rarely exceeding 3.5 cm. Therefore, heartwood production appears to begin at a relatively young age in western redcedar, perhaps 10-15 years. The amount and proportion of heartwood increased with distance downward from the top of the tree, with the implication that older trees contain a greater proportion of heartwood. For any given age, it appears that cultural treatments that favor rapid rowth result in stems with more sapwood and heartwood, and a greater proportion of heartwood.

INTRODUCTION

Western redcedar (Thuja plicata Donn) is a commercially valuable tree species in the northwestern United States and southwestern Canada. In the U.S., few landowners actively regenerate and manage redcedar, except for small scale plantings in localized areas. However, interest is increasing for a number of reasons, including concerns for biodiversity, western redcedar's resistance to laminated root rot (*Phellinus weirii* (Murrill) R.L. Gilbertson), and the declining availability of old-growth redcedar.

Because foresters in the region have limited experience managing redcedar, there is little information on variation in stem characteristics of trees grown in managed stands. Stem characteristics are usually influenced by tree spacing or other cultural practices; some of these characteristics affect the suitability of logs for conversion into useful products. The suitability of wood for end use is often referred to as "wood quality". One of the most important wood quality characteristics of western redcedar is its heartwood. It is the heartwood which possesses the color, scent, and decay resistance that makes western redcedar wood desirable. Sapwood is undesirable for most uses of western redcedar, because the chemical characteristics that make redcedar valuable are not found in the sapwood. Thus, from the standpoint of wood quality, narrow sapwood with a high proportion of heartwood is a desirable characteristic in redcedar logs.

In a search of the literature, we found few references addressing heartwood/sapwood relationships in western redcedar. The objective of this study is to evaluate those relationships within western redcedar trees and between trees grown under different cultural practices.

METHODS

We studied heartwood/sapwood relationships at three different sites. At Clatskanie, Oregon, we could sample trees destructively, so we used this site to study within-tree relationships. Maple Ridge, British Columbia and Ozette, Washington were both existing silvicultural trials, so we restricted our sampling to increment cores at those sites, and studied effects of cultural practices and growth rate on heartwood/sapwood relationships.

Clatskanie, Oregon

The study site was a second-growth stand of western redcedar, Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco), and western hemlock (Tsuga heterophylla (Raf.) Sarg.) growing near Clatskanie, Oregon, on land owned and managed by the Oregon State University College of Forestry. Eleven western redcedar trees were felled in August 1993; total height was measured, then disks were cut every 2 m from breast height (1.37m) to the top of the tree. The disks were taken to the lab, where they were air dried. Selected tree characteristics are listed in Table 5.1.

For each disk, the total diameter inside bark and the heartwood diameter were each measured first along the longest axis, and then perpendicular to the longest axis (to the nearest mm). Cross-sectional areas for both the whole disk and the heartwood portion were calculated assuming an elliptical stem cross section; sapwood width was also calculated:

Total Disk Area = $\pi(D_1D_2/4)$ Heartwood Area = $\pi(d_1d_2/4)$

Sapwood Width = $(D_1+D_2-d_1-d_2)/4$

where D_1 is the total diameter (i.b.) along the longer axis
D_2 is the total diameter (i.b.) along the shorter axis
d_1 is the heartwood diameter along the longer axis
d_2 is the heartwood diameter along the shorter axis

Table 5.1. Selected characteristics of sample trees, Clatskanie, Oregon.

Tree	Total Height (m)	BH Age	Crown Length (m)	DBH (cm)
A	36.2	91	13.0	52.6
B	39.3	*	26.0	87.0
C	34.6	*	15.5	67.6
D	35.2	*	15.5	68.8
E	33.8	95	15.0	47.8
F	30.8	93	12.0	33.4
G	34.8	*	16.5	57.3
H	32.4	92	15.0	50.2
I	28.7	*	13.5	43.2
J	36.0	94	16.5	62.6
K	30.8	*	13.5	67.2

* breast-height disk was decayed in center, so accurate ring count was not possible

Sapwood area was calculated by subtracting heartwood area from total disk area. Total number of rings, and the number of sapwood rings were recorded. Average sapwood ring width was calculated by dividing sapwood width by number of sapwood rings. We used regression analysis to characterize patterns of variation in heartwood and sapwood with increasing distance from the pith.

Maple Ridge, British Columbia

The study site was a 35-year-old western redcedar spacing trial on the University of British Columbia Research Forest, near Maple Ridge, British Columbia. Reukema and Smith (1987) give a complete description. Site index (SI_{100}) for western redcedar is estimated to be 40 m; corresponding 50-yr site index for Douglas-fir is about 43 m. The trial, established in the spring of 1959, includes five spacings (0.9, 1.8, 2.7, 3.7, and 4.6 meters), in a randomized complete block design with two replications. Each plot consists of 49 trees planted at a square spacing. There are no buffers on the plots; to reduce edge effects, measurements were made only on the inner 25 tree block of each plot. All spacings were measured except the 0.9 m spacing, which was excluded because heavy mortality left few trees to measure. All field measurements were made in August 1993.

For each tree, stem circumference at breast height was measured using a steel tape. Also, an 8 mm diameter increment core was extracted from the side of the tree facing the plot center. This sampling scheme was used to avoid any bias caused by taking all cores from the same aspect. On fluted trees, we made an effort to avoid flutes; sapwood is very narrow in the flutes and unusually wide on the adjacent ridges. On trees where fluting was severe and could not be avoided, we tried to take the core at a point intermediate between the center of the flute and the ridges bordering the flute.

Sapwood width (to the nearest mm) was measured on the core, and bark thickness (to nearest mm) was measured with a narrow ruler at the increment core hole. Total radius was calculated from stem circumference data, and sapwood width and bark thickness were used to allocate that total radius into heartwood, sapwood and bark portions. That information was used to calculate basal area of heartwood and sapwood. In the lab, the number of sapwood rings was recorded after surfacing the cores to facilitate ring counting; average sapwood ring width was calculated by dividing sapwood width by number of sapwood rings. We tested for differences among spacings using Fisher's Protected LSD test.

Ozette, Washington

The study site was an approximately 30-year-old naturally regenerated western redcedar stand near Lake Ozette on the Olympic Peninsula in Washington. Harrington and Wierman (1985) give a complete description. Site index for western redcedar (SI_{50}) is estimated to be 18-22 m. The stand regenerated after logging in 1961 to almost pure western redcedar (95% or more by basal area). In 1980, a thinning and fertilization study was installed. Seven treatments with four replications per treatment were arranged in a completely randomized design. Thinning occurred in October 1980, and fertilizer was applied in March and April 1981.

We selected four of the treatments to sample for our study. They are: 1) unthinned, unfertilized (control); 2) thinned, unfertilized; 3) unthinned, fertilized; and 4) thinned, fertilized. Plots receiving the thinning treatment were thinned to about a 3x3 m spacing (approximately 1100 trees/ha). Fertilized plots received a combination of ammonium nitrate, monodicalcium phospate, and potassium sulfate. This supplied the following elements and rates of application (kg/ha): N (300), P (100), Ca (129), K (100) and S (41).

Prior to treatment, there was a wide range in tree size. In order to minimize pretreatment differences between trees, we restricted our sampling to those trees that had diameters of 5-7 cm before treatment. We then assumed that any current differences between trees had developed primarily after treatment. From the trees that fit within the pre-treatment diameter range, we sampled about 50 trees from each treatment; trees were selected to cover the widest range of post-treatment growth rates available within each treatment.

In September 1993, we extracted an 8 mm increment core at breast height from each tree. The cores were taken back to the lab, where measurements were made. Compared with the Maple Ridge site, the Ozette trees were smaller and closer to perfectly circular in cross-section. This made it much easier to hit the pith consistently, and therefore to get an accurate direct measurement of heartwood radius from the core. So we measured heartwood radius and sapwood width on the core, and used these numbers to calculate basal areas of heartwood and sapwood. Number of sapwood rings was also recorded, and average sapwood ring width was calculated by dividing sapwood width by number of sapwood rings. We used regression analysis to assess effects of growth rate within treatments, and tested for differences between treatments in those effects using comparison of regression lines.

RESULTS

Clatskanie, Oregon

Sapwood width varied from 1.5 to 3.2 cm along the stem. From the top of the tree, sapwood width increased slightly to about 10 m below the terminal, then decreased gradually toward the base of the tree (Figure 5.1a). Although sapwood width decreased slightly down the stem, sapwood area increased over the same distance (Figure 5.1b).

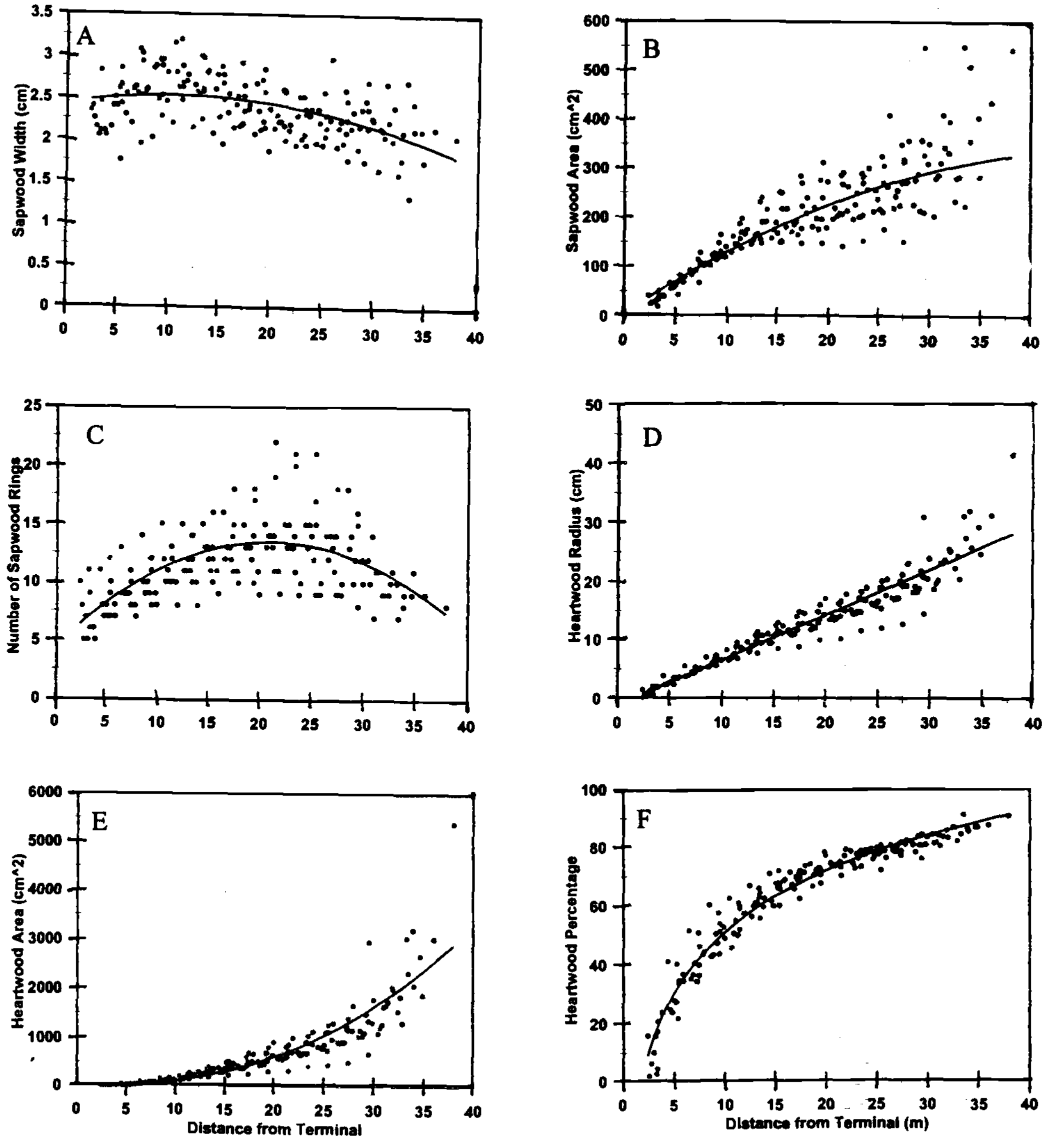

Figure 5.1. Patterns in heartwood/sapwood relationships with distance from the terminal for trees at Clatskanie, OR.

The number of sapwood rings varied from 5 to 23, and was greatest about 2/3 of the way down the stem (Figure 5.1c). Heartwood radius, heartwood area and heartwood percentage all increased from the top of the tree downward (Figure 5.1d,e,f). Number of sapwood rings was negatively related to average sapwood ring width (Figure 5.2a).

Maple Ridge, British Columbia

On an individual tree basis, there were statistically significant differences in sapwood and heartwood characteristics between spacings (Table 5.2). As tree spacing increased from 1.8 m to 4.6 m, tree diameter increased from 19.4-39.5 cm, number of sapwood rings decreased from 11.5-6.4 rings, sapwood thickness increased from 1.7- 2.7 cm, sapwood basal area increased from 92-303 cm^2 , heartwood radius increased from 7.5-16.2 cm, and heartwood basal area increased from 190-875 cm^2. There was a trend of increase in heartwood percentage from 66.4-73.1, but the differences were not statistically significant. Number of sapwood rings was negatively related to average sapwood ring width (Figure 5.2b).

On a per hectare basis, differences in sapwood and heartwood characteristics between spacings were not statistically significant (Table 5.3), although there appeared to be some trends in the data, such as higher basal areas at closer spacings and slightly higher heartwood percentages at wider spacings.

Ozette, Washington

As tree diameter increased from 8 cm to 20 cm, sapwood width increased from 1.5 to 2.5 cm, sapwood basal area increased from 20 cm^2 to 130 cm^2, heartwood radius increased from 2.5 cm to 7.5 cm, heartwood basal area increased from 15 cm^2 to 175 cm^2,

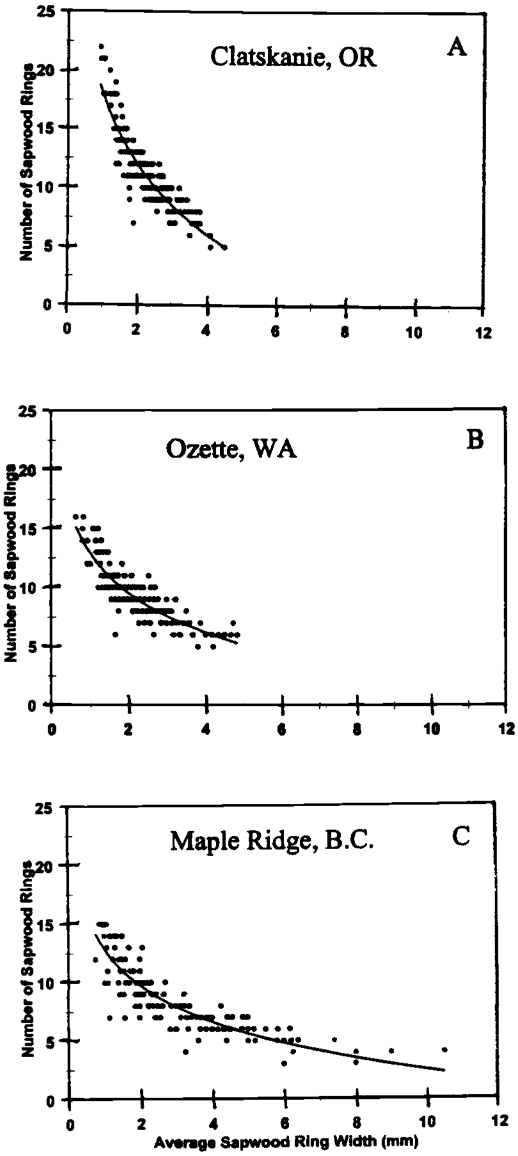

Figure 5.2. Relationship of number of sapwood rings to average sapwood ring width for all three study sites.

Table 5.2. Individual-tree sapwood and heartwood characteristics by spacing for Maple Ridge, B.C. plots. Data shown are means, with standard deviation in parentheses. Treatment means followed by the same lower case letter are not significantly different at $\alpha = 0.05$.

Spacing	1.8	2.7	3.7	4.6
		DBH (cm)		
Block 1	20.8 *(6.1)*	31.6 *(10.8)*	30.2 *(9.0)*	39.1 *(7.2)*
Block 2	18.0 *(3.4)*	25.0 *(7.0)*	36.6 *(11.4)*	39.9 *(10.5)*
Total	**19.4** *a*	**28.3** *ab*	**33.4** *bc*	**39.5** *c*
		Number of Sapwood Rings		
Block 1	11.2 *(2.5)*	8.4 *(2.5)*	7.9 *(1.9)*	6.4 *(1.1)*
Block 2	11.9 *(2.4)*	10.3 *(2.7)*	6.5 *(1.8)*	6.4 *(2.0)*
Total	**11.5** *a*	**9.3** *ab*	**7.2** *bc*	**6.4** *c*
		Sapwood Thickness (cm)		
Block 1	1.9 *(0.4)*	2.1 *(0.6)*	2.3 *(0.6)*	2.8 *(0.6)*
Block 2	1.5 *(0.3)*	2.0 *(0.4)*	2.3 *(0.5)*	2.5 *(0.6)*
Total	**1.7** *a*	**2.0** *ab*	**2.3** *bc*	**2.7** *c*
		Sapwood Basal Area (cm^2)		
Block 1	110 *(55)*	198 *(110)*	202 *(98)*	313 *(110)*
Block 2	74 *(27)*	137 *(56)*	248 *(102)*	293 *(127)*
Total	**92** *a*	**168** *ab*	**225** *bc*	**303** *c*
		Heartwood Radius (cm)		
Block 1	7.9 *(2.6)*	12.9 *(5.0)*	12.0 *(3.9)*	15.8 *(3.2)*
Block 2	7.1 *(1.4)*	9.9 *(3.2)*	15.3 *(5.3)*	16.6 *(4.8)*
Total	**7.5** *a*	**11.4** *ab*	**13.7** *bc*	**16.2** *c*
		Heartwood Basal Area (cm^2)		
Block 1	215 *(140)*	597 *(376)*	501 *(281)*	811 *(324)*
Block 2	165 *(66)*	338 *(196)*	818 *(486)*	939 *(460)*
Total	**190** *a*	**468** *ab*	**660** *b*	**875** *b*
		Heartwood Percentage		
Block 1	63.9 *(6.7)*	71.4 *(9.9)*	69.1 *(6.9)*	71.5 *(3.9)*
Block 2	68.9 *(5.0)*	68.2 *(7.4)*	73.8 *(7.4)*	74.7 *(6.5)*
Total	**66.4** *a*	**69.8** *a*	**71.4** *a*	**73.1** *a*

Table 5.3. Per hectare sapwood and heartwood characteristics by treatment for Maple Ridge, British Columbia plots. Treatment means followed by the same lower case letter are not significantly different at $\alpha = 0.05$.

Spacing	1.8	2.7	3.7	4.6
Live Trees per Hectare				
Block 1	2272	904	747	459
Block 2	1794	1063	538	459
Total	**2033** a	**983** *b*	**643** *b*	**459** *b*
Sapwood Basal Area (m^2/ha)				
Block 1	26.2	17.9	15.1	14.4
Block 2	13.2	14.6	14.8	13.5
Total	**19.7** a	**16.3** a	**15** a	**13.9** a
Heartwood Basal Area (m^2/ha)				
Block 1	51.4	54.0	37.5	37.3
Block 2	29.6	36.0	48.9	43.1
Total	**40.6** a	**45.0** a	**43.2** a	**40.2** a
Total Basal Area Inside Bark (m^2/ha)				
Block 1	77.6	71.9	52.6	51.6
Block 2	42.9	50.6	63.7	56.6
Total	**60.2** a	**61.2** a	**58.1** a	**54.1** a
Heartwood Percentage				
Block 1	66	75	71	72
Block 2	69	71	77	76
Total	**68** a	**73** a	**74** a	**74** a

and heartwood percentage increased from 40% to 58% (Figure 5.3). For a given diameter, trees on fertilized plots had less sapwood and more heartwood than trees on unfertilized plots; the magnitude of this difference for heartwood percentage was 5-8%, depending on tree diameter. For fertilized treatments, the relationship of heartwood and sapwood characteristics to tree diameter was not affected by thinning. For unfertilized trees, the relationship of sapwood thickness and heartwood radius to tree diameter was somewhat different for thinned and unthinned treatments. However, there was no such difference for sapwood or heartwood areas or heartwood percentage.

DISCUSSION

Within-tree variation

Sapwood area at a given height in the tree has been shown in many species to be related to the leaf area or leaf mass above that point, because a key function of sapwood is to supply the foliage above with water (Waring et al. 1982). Maintaining more sapwood area than is necessary would be detrimental to the tree's carbon balance, due the respiration costs of live parenchyma cells in the sapwood (Ryan 1989). When stem cross-sectional area exceeds the sapwood area required to supply the crown above with water, the excess area can be converted to heartwood (Long et al. 1981). In the trees from Clatskanie, this point of inital heartwood formation was about 3 m below the terminal (Figure 5.1d); at this height, there were 10-15 annual rings in the stem cross-section. If the same is true of younger redcedar trees, this suggests that heartwood formation begins at a relatively young age in western redcedar. The Ozette trees, which were about 30 years old, already contained heartwood with radii from 2-8 cm at breast height, depending on tree diameter (Figure 5.3b). Average heartwood radius at breast height in the Maple Ridge trees, which were 35 years old, ranged from 7.5 to 16.2 cm, depending on tree spacing (Table 5.2). In the 384 trees that we measured at the three sites, sapwood width

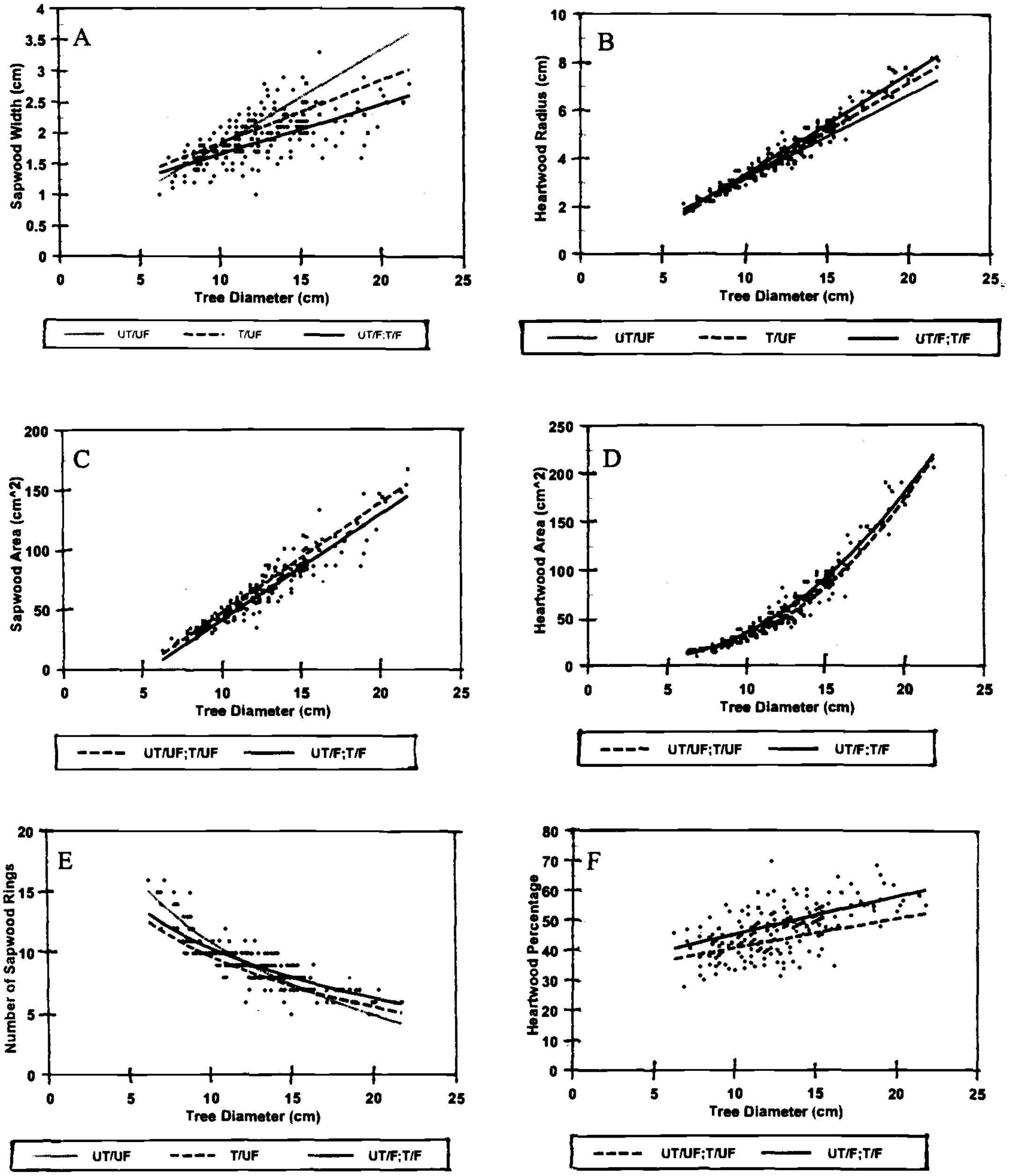

Figure 5.3. Heartwood and sapwood characteristics vs. tree diameter at Ozette, Washington. Separate regression lines are shown for treatments that were significantly different from one another.

rarely exceeded 3.5 cm, suggesting that trees larger than about 7 cm at a given height can be expected to contain heartwood at that height.

Our data showed a rapid increase in sapwood area from the terminal downward for about 12 m, followed by a slower increase with more variability lower in the stem (Figure 5.1b). The greater spread in the data points further down the stem is likely due to differences between trees affecting the lower stem that did not exist higher in the crown. One obvious difference between trees is crown length (Table 5.1); this would create differences between trees in sapwood area lower in the stem. Another difference may be the permeability of the sapwood. There were large differences between trees in sapwood ring width in the lower part of the stem; if these differences affect wood permeability, there could be differences between trees in the leaf area to sapwood area ratio (Espinosa Bancalari et al. 1987). The very high values for sapwood area (>400 cm^2) came from disks near the base of heavily fluted trees; because sapwood width becomes extremely narrow in the flutes, our method of estimating sapwood area probably overestimated sapwood area in very fluted trees.

While sapwood area increased from the terminal downward, sapwood width increased only a short distance down the stem, then actually decreased for most of the distance toward the base. (Figure 5.1a) This pattern of variation in sapwood width results from the patterns in sapwood area described above. In the uppermost part of the crown, sapwood area is increasing rapidly with distance from the terminal; stem diameter is fairly small in this part of the tree, so sapwood width must increase to supply the sapwood area needed to support the crown above. Two factors allow sapwood width to decrease further down the stem. The first is that sapwood area, which increases rapidly down through the live crown, increases more slowly below the base of the crown (Waring et al. 1982; Espinosa Bancalari et al. 1987). The second is that stem diameter continues to increase down the stem; on a large diameter stem, even a fairly narrow band of sapwood represents a considerable cross-sectional area. Thus, sapwood width can actually decrease along the stem while the required sapwood area is maintained. Sapwood widths observed in this study are similar in both magnitude and pattern of variation along the stem to those reported for western redcedar by Wellwood and Jurazs (1968), who studied 73 western redcedar trees ranging in age from 40 to 237 years. Our results differ from those reported (Pinus banksiana Lamb.) and tamarack (Larix laricina (Du Roi) K. Koch); in a study involving ten trees of each species, sapwood width was found to vary little among different heights in the stem (Yang et al. 1985).

The number of sapwood rings at a particular height is influenced by sapwood width and average ring width of the outer rings at that height. Ring width is probably the more important factor, since variation in ring width is generally much greater than variation in sapwood width. The inverse relationship between average ring width and number of sapwood rings is evident in data from all three sites (Figure 5.2). Similar results have reported for jack pine and tamarack(Yang et al. 1985).

Heartwood radius, area and percentage increased with distance from the terminal (Figure 5.1). The implication of this is that older trees can be expected to contain a higher proportion of heartwood, since older trees have a larger proportion of their volume at distances far from the terminal. Therefore, rotation length will affect the proportion of stand volume that is heartwood.

Influence of cultural practices - individual tree relationships

Since sapwood area is related to leaf area, sapwood area can be influenced by practices that affect leaf area. For instance, wider spacings result in larger crowns, and therefore larger sapwood areas (Table 5.2). Sapwood width is wider as well, but the magnitude of the increase is much less than that for sapwood area. In the Maple Ridge trees, sapwood basal area per tree increased by 230%, while sapwood width increased by only 60%, over the range of spacings studied (Table 5.2). Similar relationships occurred in the Ozette trees, where sapwood basal area increased by 600% while sapwood width only increased by 80% from the smallest to largest diameter trees (Figure 5.3). Since the Ozette trees were all nearly the same age, stem diameter serves as an indicator of crown size and vigor.

The reason that sapwood width does not increase more is a matter of geometry. Large crowned trees require more sapwood area, but they also grow faster in diameter. As tree diameter increases, the sapwood is distributed on larger cylinders, and modest increases in sapwood width create large increases in sapwood area.

Faster growing trees and trees grown at wider spacings had fewer sapwood rings compared to slower-growing trees or trees grown at close spacings, despite having wider sapwood (Figure 5.3; Table 5.2). This is explained by the wider rings of faster-growing trees.

Other studies have reported similar relationships of sapwood to spacing or growth rate. Wang and Chen (1992) studied 40-year-old Cryptomeria japonica D. Don growing at spacings from 1x1 m to 5x5 m, and found a positive relationship between tree diameter and sapwood width. Wilkins (1991) found that silvicultural treatments that increased growth rate resulted in wider sapwood and greater sapwood area in Eucalyptus grandis (Hill) Maiden. Yang and Hazenberg (1992) studied 38-year-old Picea mariana (Mill.) B.S.P. and Picea glauca (Moench.) Voss grown at spacings from 1.8 m x 1.8 m to 3.6 m x 3.6 m, and reported that trees in wider spacings had fewer sapwood rings, wider sapwood, and greater sapwood area.

Heartwood radius and area are also increased by conditions that favor rapid growth, such as wide spacing. As discussed above, fast growth creates a larger cylinder on which the sapwood is distributed. So, as stem diameter increases, sapwood width can actually decrease if sapwood area does not increase. Heartwood radius can then increase in proportion to stem growth plus decrease in sapwood width. Our findings that heartwood radius and area are greater with faster growth or wider spacing are consistent with data for Picea glauca and Picea mariana (Yang and Hazenburg 1992).

The percentage of heartwood increased with diameter growth rate at Ozette (Figure 5.3f) and appeared to increase somewhat with spacing at Maple Ridge, although that relationship was not statistically significant (Table 5.2). We believe that the differences at Maple Ridge were real, despite the lack of statistical significance. There were large and significant diffferences in tree diameter between spacings (Table 5.2); heartwood percentage was positively related to tree diameter at Maple Ridge, just as it was at Ozette (although we don't present the Maple Ridge data that way in this paper). Thus we believe the lack of significance at Maple Ridge can be attributed to having only two replications, and the relatively small magnitude of the difference in heartwood percentage between spacings. Our results are similar to those of Wang and Chen (1992), who found that heartwood percentage increased with tree spacing in Cryptomeria japonica.

Similar results have been reported in Eucalyptus grandis; Wilkins (1991) found that silvicultural treatments that increased growth rate resulted in a greater heartwood area and higher percentage of heartwood. From the standpoint of producing the greatest proportion of heartwood, spacings which result in rapid growth rates are most desirable. This must be weighed against other factors influencing stand value, such total volume produced.

Fertilization had a statistically significant influence on heartwood/sapwood relationships at Ozette, even after taking into account differences due to growth rate. Trees in fertilized treatments had less sapwood and more heartwood than trees of comparable size growing in unfertilized treatments. We are unsure of the reasons for this, but we offer some possible explanations. We restricted our sampling to trees that were approximately the same size before treatment, so trees of a given current diameter should have grown approximately the same amount since treatment. The fact that fertilized trees of a given diameter had less sapwood than unfertilized trees of the same diameter suggests that either: **1)** fertilized trees accomplished that stem growth with less leaf area than their unfertilized counterparts, and the leaf area to sapwood area ratio was the same for both treatments, or **2)** the amount of leaf area required to support a given amount of growth was the same for both fertilized and unfertilized treatments, but the leaf area to sapwood area ratio was higher for fertilized treatments. We do not have the data to evaluate these possibilities, but offer these speculative explanations as ideas for further research.

Either explanation seems plausible based on past research. Espinosa Bancalari et al. (1987) found that the leaf area to sapwood area ratio varied substantially between adjacent Douglas-fir stands growing at different rates. However, Whitehead et al. (1984) found no difference in leaf area to sapwood area ratios between sitka spruce (Picea sitchensis (Bong.) Carr.) trees fertilized with potassium and phosphorus and unfertilized trees. If the leaf area to sapwood area ratios in the trees we studied did not differ in response to fertilization, then fertilized trees must have grown to a given size with less leaf area than their unfertilized counterparts. Several mechanisms might explain a higher growth per unit of leaf area in fertilized trees, such as higher rates of photosynthesis in fertilized trees, or more carbon allocation to roots rather than stems in unfertilized trees (Hinckley et al. 1992).

Influence of cultural practices - per hectare relationships

Although there were not statistically significant differences in heartwood and sapwood characteristics on a per hectare basis, there appear to be some trends. For instance, sapwood basal area and total basal area tended to be greatest at close spacings, while percentage heartwood tended to be largest at wider spacings. Higher per hectare basal area values at close spacings would be consistent with other studies (Reukema and Smith 1987; Hoyer and Swanzy 1986), and higher percentage heartwood at wider spacings is consistent with the individual tree data for both Maple Ridge and Ozette. With only two replications and high variability between plots at a given spacing, it is not surprising that the relationships are not significant. Based on the data available, a reasonable conclusion is that wider spacings are at least comparable to closer spacings in the total basal area of heartwood produced; wider spacings may contain a slightly higher percentage of heartwood and slightly less absolute heartwood basal area. Furthermore, the heartwood is concentrated in fewer, larger stems at wide spacings; presumably this will result in more recoverable heartwood in solid wood products.

Management implications

Western redcedar is valued primarily for the properties of its heartwood. Therefore, the quantity of heartwood produced is of interest from the standpoint of wood quality. It appears that heartwood production begins at a fairly young age, perhaps as early as 10-15 years. The proportion of heartwood increases with tree age, so rotation length will have an influence on the amount of heartwood for a given stand volume. For any given rotation length, practices that encourage rapid growth, such as wide spacings or fertilization, will likely increase the proportion of heartwood on an individual tree basis, and possibly on a per hectare basis.

Chapter 6: Conclusions

The preceding chapters document variation in several wood quality characteristics in second-growth western redcedar stands, and how some cultural practices can be used to affect those characteristics.

Stem morphological characteristics such as branch size, taper and fluting increased with tree spacing. Tropolone content and decay resistance varied substantially within the stem, with the lowest levels of each usually found in wood near the pith or the top of the tree. Wood with high tropolone content had high decay resistance in soil block tests, while wood with low tropolone content was extremely variable in decay resistance. Heartwood and sapwood relationships varied both within the stem and between trees subjected to different cultural treatments. Within the stem, the quantity and proportion of heartwood increased from the top of the tree downward. Trees that grew faster as a result of cultural treatments had more sapwood and heartwood, and tended to have a higher proportion of heartwood compared to their slower-growing counterparts.

The conclusions above show that forest managers have some degree of control over many wood quality characteristics in western redcedar, through selection of cultural treatments and rotation length.

The most important area on which to focus future research is probably the factors influencing tropolone content. Much of the value of western redcedar stems from the decay resistance of the heartwood, due largely to the fungicidal properties of the tropolones. This research has demonstrated large differences between trees in patterns of variation of tropolone content with age. A better understanding of the reasons behind these differences might allow forest managers to grow trees of higher decay resistance, thus maintaining highly decay resistant wood for products or wildlife structures.

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